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FINAL TECHNICAL REPORT
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Summary of Scientific Achievements

During the tenure of NASA grant NGR-33-008-199 we have mainly been concerned with various aspects of the petrology of Apollo 14 breccias. Some of the scientific results are contained in the following publications which are appended.

1. Petrologic studies of poikiloblastic textured rocks.
2. Petrology of aluminous mare basalts in breccia 14063.
3. Petrology of Apollo 15 breccia 15459.
4. On high-alumina mare basalts.
5. Some petrological aspects of Imbrium stratigraphy.
6. Petrology of lunar rocks and implication to lunar evolution.

In addition some funds have been used to support work in comparative planetology as shown in the following appended publications.

1. The crystallization trends of spinels in Tertiary basalts from Rhum and Muck and their petrogenetic significance.
2. The geology and evolution of the Cayman Trench.
3. The petrochemistry of igneous rocks from the Cayman Trench and the Captains Bay Pluton, Unalaska Island: Their relation to tectonic processes at plate margins.
4. The oxide and silicate mineral chemistry of a Kimberlite from the Premier Mine: Implications for the evolution of kimberlitic magma.

Publication #3 takes the form of a large Ph.D. thesis by M.R. Perfit; in this report the abstract, map and data base are appended.

We also have a significant amount of unpublished data on Apollo 14 poikiloblastic rocks which are discussed below and the data and figures appended.

During the last year we have concentrated our studies on poikiloblastic-textured clasts in the Apollo 14 breccias, which although recognized at the time of the preliminary descriptions, had not been quantitatively studied. A great deal of controversy has surrounded the interpretation of poikiloblastic clasts in the highland breccias returned from the Apollo 16, 17 and Luna 20 missions. Several mechanisms, rather than one unique process, might be invoked to completely explain the variety of poikilitic textures observed. Such clasts have been interpreted as the products of metamorphic reheating, subsolidus recrystallization during cooling, or of "igneous" origin. Melts associated with the latter process have been considered endogenetic (Steele and Smith, 1973; Crawford and Hollister, 1974; Schonfeld and Mayer, 1973; Ashwal, 1975) or of impact origin (Grieve, 1975; Irving, 1975; Simonds, 1975). Complicating matters is the confusing state of knowledge regarding the development of the poikilitic texture in terrestrial rocks, e.g., Wager (1961) has proposed that poikilitic textures form as a result of a two stage cooling process involving an initial rapid temperature decrease followed by a gradual decrease. Simonds et al. (1973) and Simonds (1975) suggest a similar cooling history for lunar casts, where in the initial stages small feldspar crystals formed, followed by coarse pyroxenes; the result of moderate nucleation and high growth rates. Alternately, Ryder and Bower (1976) suggest that poikilitic textures may result from growth at numerous nucleation sites centered on small plagioclase fragments.

In studying clastic rocks from the Apollo 16, 17 and Luna 20 sites, Albee et al. (1973) concluded that extensive metamorphism at about 3.95 AE of clastic, surficial rocks, led to the growth of coarse-grained predominantly low-Ca pyroxene oikocrysts, surrounding relict matrix

chadacrysts. Such metamorphism might have occurred in thick ejecta blankets from large impact events. Bence et al. (1973) and Hodges et al. (1973) also proposed that pyroxena oikocrysts grew by solid-state recrystallization (the poikilitic textures can be simulated experimentally by sintering of glasses), in the presence of a small volume of melt during high-grade metamorphism. Bence et al. (1974) concluded that in the case of noritic breccia 77135, extensive melt may have been produced during anatexis of the rock, resulting in abundant pigeonite and a vesicular structure.

Staale and Smith (1973) suggest early, widespread crustal melting of the moon, accompanied by recrystallization and metamorphism, to account for the textures in the Apollo 16 terra rocks and fines. Similarly, Roedder and Waiblen (1974) presume that metamorphism explains coarse-grained clasts in breccia 67915, involving a series of partial melting and recrystallization events as described by Walter et al. (1973).

McCallum et al. (1974), using experimental data and various mineral geothermometers, deduced that poikilitic breccia 77017, crystallized between 1050-1100°C, at least 100°C below the solidus. Hence, although 77017 bulk composition is indicative of a terra cumulate, impact reworking and metamorphism obliterated the original texture. Using similar mineral geothermometers, Ridley (1976) arrived at a temperature below 1100°C for a poikilitic anorthositic gabbro clast in breccia 15459.

In contrast, cases have also been argued in favor of crystallization directly from a melt. Hollister (1973) concluded that poikilitic hypersthene and diopside in breccia 67955 resulted from a high temperature crystallization from a silicate melt. Similarly, Schaeffer and Hollister

(1975) believe that clasts in 60255 cooled at varying rates from a melt, and Crawford and Hollister (1974) arrive at a similar conclusion for poikilitic clasts in 62235. Ashwal (1975) presents chemical and textural evidence that poikilitic clasts in anorthositic norites 67955 and 77017 resulted from plutonic crystallization from a silicate melt. The crystallization history involved initial crystallization of anorthite, followed by olivine at the plagioclase-olivine cotectic. Olivine reacted with residual liquid to form low-Ca pyroxene and at this stage pyroxene oikocrysts grew, surrounding partly resorbed olivine and previously formed plagioclase.

The above discussions have emphasized the endogenic nature of the silicate melt, but an impact melt origin is equally strongly advocated. Simonds et al. (1973), in their studies on Apollo 16 KREEP compositions, advocated crystallization from an impact partial melt by rapid cooling to the plagioclase-olivine cotectic. Slower cooling to the peritectic results in olivine resorption, further plagioclase growth and eventually nucleation of pyroxene. The slow cooling is facilitated by mantling and insulation by further ejecta, where initial rapid cooling might result from heat loss from the hot, turbulent impact melt to cold, swept-up surface debris. Irving (1975) and James (1976) generally support this view. Simonds et al. (1976) have made comparisons with the Manicouagan impact structure in Quebec, noting a number of textural similarities to lunar poikilitic rocks. Terrestrial impact analogs have also been described by Grieve et al. (1974) and Grieve (1975).

Figure 1

Variations in composition of zoned pyroxene oikocrysts in Apollo 14 poikilitic-textured clasts. The size of triangles indicates the relative amounts of pyroxene components incorporating Al, Cr and Ti. Arrows indicate generalised zoning trends from core to rim. From left to right samples are 14066, 36; 14066, 51 (triangles with squares); 14066, 49; 14307, 42; 14305, 107 (filled triangles).

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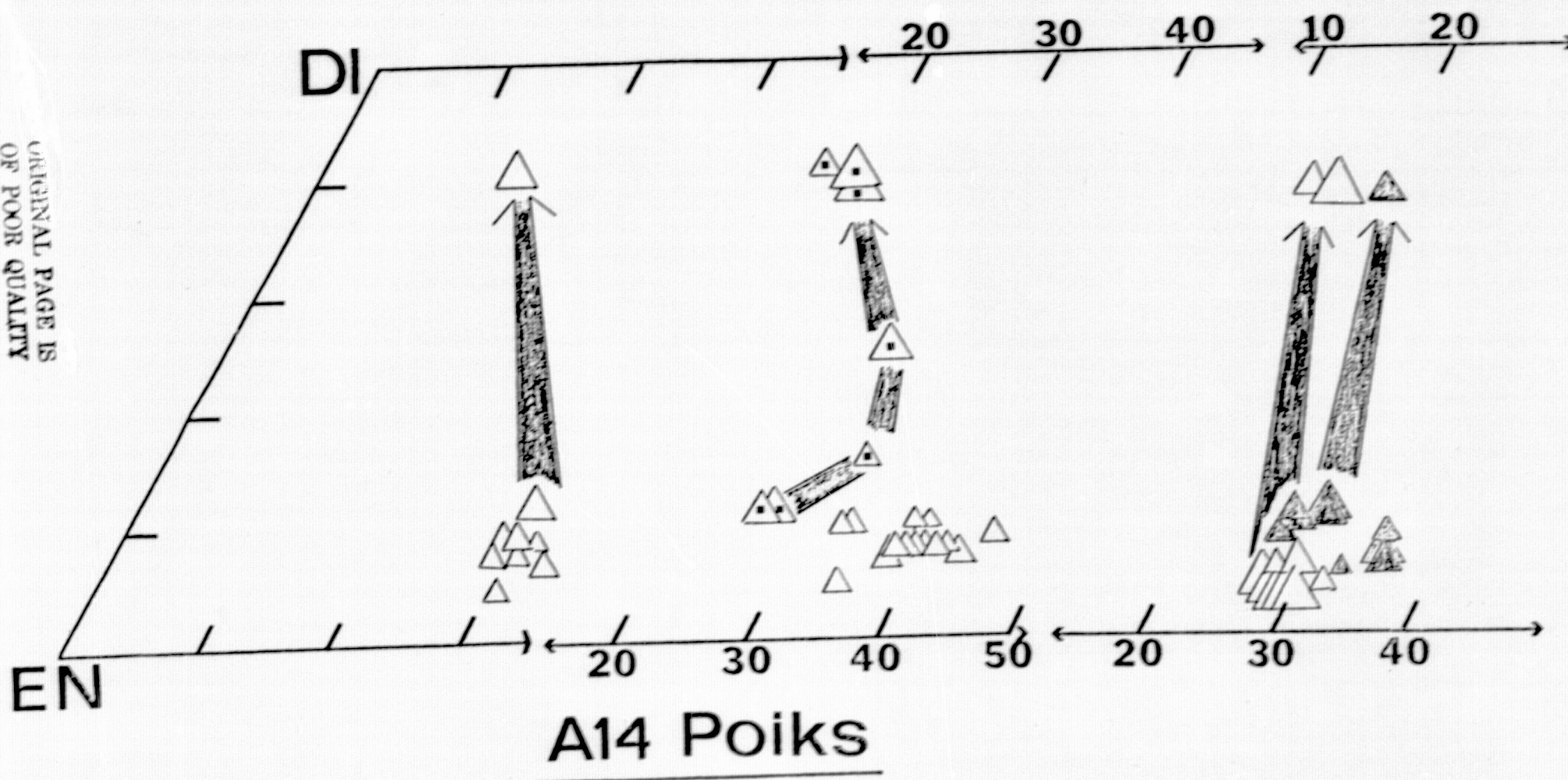


TABLE 1. Ion-microprobe Measurements on Apollo 14 Plagioclases

p.p.m.	<u>Li</u>	<u>Ti</u>	<u>Sr</u>	<u>Ba</u>
1. <u>Cataclastic anorthosites</u>				
	20	225	337	460
	22	202	382	525
2. <u>High-alumina basalt</u>				
	17	346	148	119
	16	301	180	258
	17	233	184	24
	17	260	192	24
	16	130	124	21
	17	364	229	287
	19	145	143	18
	15	143	130	113
	13	267	128	32
	10	236	146	84
	13	232	141	68
	21	285	168	27
3. <u>Peikilitic rocks</u>				
	16	190	288	456
	12	186	261	369
	13	136	267	391
	12	245	271	550
	20	563	270	770
4. <u>Plagioclase ass. w. pink spinel</u>				
	8	17	320	49
5. <u>Plagioclase clasts</u>				
	23	274	377	654
	12	172	311	195
	20	211	413	358
	28	224	504	769
	36	228	514	854
	31	271	467	619
	10	146	304	283
6. <u>Lake County Plagioclase</u>				
	4	230	582	63

Only a few descriptions of poikilitic-textured clasts from Apollo 14 rocks have been made. These include studies by Duncan et al. (1975), Grieva et al. (1975), Ryder and Bower (1976). Interpretations likewise cover the gamut from sub-solidus recrystallization to crystallization from a silicate melt. We have observed poikilitic-textured clasts in samples 14066, 14305, 14307. Selected mineral analyses and bulk analyses are shown in the enclosed appendix. Variations in pyroxene oikocryst compositions are shown in Figure 1. The common zoning trends indicate initial crystallization of low-Ca pyroxene (perhaps hypersthene), followed by augite. However, some oikocrysts are either all low-Ca pyroxene or augite and show little compositional variability. This may indicate an extended period of oikocryst nucleation and/or local bulk composition control on the crystallizing pyroxene.

Some of the Apollo 14 poikilitic samples have also been examined by ion microprobe, with particular reference to the trace element compositions of plagioclase. Also analyzed were individual plagioclase clasts in breccia matrix, plagioclases in clasts of high-alumina basalt (KREEP?), plagioclase in cataclastic anorthosites and plagioclase associated with pink spinel. Data are shown in Table 1.

Texturally the poikilitic rocks are simpler than those described from other terra sites. The most complex types are those observed in the Apollo 15 breccias, as described by Ridley (1976) in that they carry several chadacryst phases (plagioclase, augite, pigeonite, olivine, alminite) and have exsolved inverted pigeonite oikocrysts. In contrast the Apollo 14 poikilitic-textured rocks have chadacrysts and xenocrysts of plagioclase only, and simply zoned pyroxene oikocrysts. In addition they do not contain the diabasic areas described from some Apollo 16 and 17

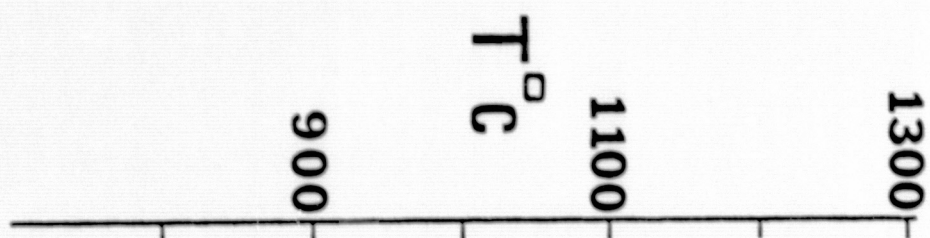
samples, so that there is no compelling evidence that they developed in the presence of a silicate melt phase.

Attempts have been made to derive temperatures of crystallization for poikilitic-textured rocks (McCallum et al., 1974), using mineral geothermometry, particularly pyroxenes. As pointed out by Hewins (1975), low diffusion rates cause pyroxene compositions to be fixed at or near peak temperatures, making them useful geothermometers. However, low diffusion rates are most likely observed in metamorphic rocks, e.g., granulites, under water-absent or water-deficient conditions. Higher diffusion rates (sufficient to re-equilibrate coexisting minerals to lower temperatures) may occur in the presence of either a volatile or a silicate melt phase. Hence in the lunar situation, mineral geothermometry is most applicable to those rocks equilibrated at "metamorphic" temperatures, and less easily applied to either totally melted rocks or poikilitic-textured rocks formed in the presence of a silicate melt phase.

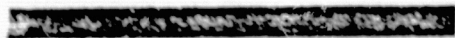
We can apply some mineral geothermometers to poikilitic textured rocks if it is assumed that 1) they developed at sub-solidus temperatures, probably similar to the anhydrous granulite-facies, involving low diffusion rates; 2) peak temperatures were maintained sufficiently long to equilibrate low-Ca pyroxenes and augite poikiloblasts; 3) temperatures were maintained sufficiently long to equilibrate olivine and augite chadocrysts (this mineralogy does not apply to Apollo 14 samples, but the assumption may be valid for clasts in 15459); 4) the mineral geothermometers are valid temperature indicators. Wood and Banno (1973) have developed a semi-empirical expressing using the composition of co-existing pyroxenes based on data from Davis and Boyd for the reaction $(Mg_2 Si_2 O_6)_{opx} \rightleftharpoons (Mg_2 Si_2 O_6)_{cpx}$.

Figure 2

Temperatures derived from coexisting pyroxenes (circles) or coexisting olivine and pyroxene (crosses) for some lunar samples. Mineral data are from McCallum et al. (1974), Albee et al. (1973), Ridley et al. (1973), Holz and Appleman (1973).



poikiloblastic rocks	x	O—O	77017
	x	O	60315
	x	O	61156
		O	15459
	x	O	
	+		68415
	+		15459



breccia
formation

Saxena and Nehru (1975) have shown that temperature errors are produced by assuming that the orthopyroxene and clinopyroxene phases are ideal two-site solutions of $\text{CaMgSi}_2\text{O}_6$ and $\text{Mg}_2\text{Si}_2\text{O}_6$. Additional errors may be produced by the site-allocation of Al, Cr, Ti and Na. Hewins (1975) concluded that this geothermometer may produce temperatures up to 50°C too high. Powell and Powell (1974) have determined temperature based upon olivine-clinopyroxene equilibration, calibrating the geothermometer against iron-titanium oxide temperatures. Although the geothermometer is pressure-dependent, this variable is assumed to be negligible in the lunar cases.

It should be stressed that temperatures derived from mineral geothermometers, at least in the lunar cases, cannot be used to define unequivocally a mode of formation of lunar poikilitic-textured rocks. At best the derived temperatures, if used in conjunction with other textural and chemical data, may indicate that some samples formed at temperatures between 1000-1100°C. Temperatures derived for samples showing evidence for the presence of a melt phase are not easily interpreted and may represent values well below the peak temperatures developed. The pyroxene geothermometer can best be applied to those Apollo 14 poikilitic rocks containing oikocrysts of either weakly zoned orthopyroxene or augite. These samples give temperatures of 1000-1100°C. Since these samples show no conclusive evidence for a melt phase (diabasic areas or vesicular structure), we assume that the poikilitic texture developed under sub-solidus, metamorphic temperatures. It should be noted that temperatures derived for other poikilitic-textured rocks, using textural evidence that mineral pairs crystallized together also give temperatures between 1000-1100°C. (Figure 1).

These may reflect peak formation conditions, e.g., 77017, or have no unique significance, e.g., 60315, 61156.

Conditions of Formation of Poikilitic-textured Rocks.

In the previous discussion we have emphasized the wide range of opinion regarding the origin of these rocks. This probably reflects a true multiplicity of origins for poikilitic-textured lunar rocks. Generally, their formation may have been associated with impact processes, involving either melt formation, or providing sub-solidus conditions in thick ejecta blankets, as also indicated by the discovery of poikilitic-textured rocks at terrestrial impact sites. However, both the textural and chemical data are consistent with other formational processes. Poikilitic-textured rocks are commonly observed in terrestrial layer intrusions and are of primary igneous origin. However, most are rather coarse-grained and texturally distinct from most lunar poikilitic rocks. Probably this igneous-cumulate origin can be eliminated for the lunar samples. Poikilitic-textured rocks are also associated with the marginal-facies of terrestrial plutons, either as hornfelsic aureoles, or as a fine-grained facies of the pluton itself. Protoclastic structures are common in these situations, as a consequence of marginal shearing, producing a combination of clastic and poikilitic textures not unlike those observed in the lunar samples. Such a mode of formation cannot be eliminated in the lunar cases since it is now generally agreed that emplacement of plutons was an important part of the early development of the lunar crust. Emplacement of plutons into the crust may have caused thermal metamorphism of the impact-brecciated country rock leading to formation of poikilitic-textured hornfels associated with clastic xenoliths and xenocrysts. Alternately,

some poikilitic-rocks may be rapidly cooled marginal facies of plutons which underwent protoclastic deformation during their formation.

Spot positions within grains are indicated by E (edge), C (centre),
I (intermediate). No letter indicates small, unzoned grains.

Table 1-8. Pyroxene oikocrysts in poikilitic clasts.

Table 9-10. Pyroxenes in mafic norites.

Table 11. Pyroxenes in equigranular norites.

Table 12-16. Pyroxenes in anorthosites.

Table 17. Ilmenites in mafic norites.

Table 18. Ilmenite chadacrysts in poikilitic clasts.

Table 19. Ilmenites in anorthosites.

Table 20-23. Plagioclase chadacrysts in poikilitic clasts.

Table 24-25. Plagioclase in anorthosites.

Table 26. Defocussed beam analyses of poikilitic clasts.

TABLE 1

14066, 51:

	1E	1I	1C	2	3	4	5	6	7E	7I	7C
SiO ₂	52.07	53.07	52.03	52.13	52.31	52.31	52.18	52.51	52.40	52.00	52.50
TiO ₂	0.71	0.64	0.78	0.71	0.69	0.74	0.74	0.67	0.65	0.70	0.81
Al ₂ O ₃	0.75	0.40	1.01	0.64	0.69	0.76	0.61	0.62	0.68	0.64	0.65
Cr ₂ O ₃	0.21	0.25	0.26	0.23	0.24	0.22	0.21	0.23	0.26	0.26	0.21
FeO	19.44	20.72	18.47	22.48	21.40	20.07	20.31	22.05	21.70	22.26	22.41
MnO	0.45	0.42	0.39	0.43	0.45	0.36	0.39	0.37	0.40	0.41	0.41
CaO	5.47	4.90	2.53	3.87	4.12	3.92	3.91	4.25	4.93	4.39	3.61
Na ₂ O	0.04	0.07	0.05	0.04	0.14	0.04	0.02	0.03	0.03	0.07	0.03
Total	100.38	101.29	99.13	100.39	101.05	100.00	99.49	101.45	101.72	100.90	101.32
Si	1.940	1.964	1.938	1.958	1.945	1.951	1.959	1.949	1.942	1.950	1.951
Ti	0.019	0.018	0.022	0.020	0.019	0.020	0.020	0.018	0.018	0.019	0.022
Al	0.033	0.017	0.044	0.028	0.030	0.033	0.027	0.027	0.029	0.028	0.028
Cr	0.006	0.007	0.007	0.007	0.007	0.006	0.006	0.006	0.007	0.007	0.006
Fe	0.606	0.641	0.575	0.706	0.665	0.626	0.637	0.684	0.672	0.694	0.696
Mn	0.014	0.013	0.012	0.013	0.014	0.011	0.012	0.011	0.012	0.012	0.012
Mg	1.177	1.145	1.310	1.110	1.164	1.198	1.180	1.144	1.140	1.120	1.144
Ca	0.218	0.194	0.101	0.155	0.164	0.156	0.157	0.169	0.195	0.175	0.143
Na	0.003	0.004	0.003	0.003	0.010	0.003	0.001	0.002	0.002	0.005	0.002
Z	4.020	4.007	4.015	4.004	4.021	4.008	4.003	4.015	4.022	4.014	4.009
Z ^{Tet}	1.973	1.981	1.982	1.986	1.975	1.984	1.986	1.978	1.971	1.978	1.979
Al ^{IV}	0.033	0.017	0.044	0.028	0.030	0.033	0.027	0.027	0.029	0.028	0.028
Others	3.0	2.3	3.7	2.8	3.1	3.0	2.6	2.6	2.7	2.9	2.8
En	59	58	66	56	59	60	60	58	57	56	58
Wo	11	10	5	8	8	8	8	8	10	9	7
Fs	30	32	29	36	33	32	32	34	33	45	35

TABLE 2

14066, 49:

	1I	1E	1E	1I	1C	2E	2C	2C
SiO ₂	49.57	48.91	49.02	49.84	49.91	50.28	51.95	52.13
TiO ₂	0.01	1.51	1.66	0.78	0.01	1.30	0.66	0.75
Al ₂ O ₃	1.53	1.60	1.51	1.40	1.20	1.86	1.49	1.56
Cr ₂ O ₃	0.41	0.42	0.44	0.38	0.48	0.58	0.55	0.55
FeC	11.32	11.86	11.58	11.80	20.31	18.23	16.70	16.30
MnO	0.09	0.31	0.28	0.49	0.01	0.41	0.35	0.44
MgO	15.17	15.04	14.79	14.86	18.22	16.16	23.35	22.83
CaO	20.81	20.23	20.82	20.61	8.17	13.24	6.13	6.55
Na ₂ O	0.12	0.11	0.12	0.06	0.01	0.05	0.02	0.02
Total	99.06	100.02	100.24	100.24	98.31	102.14	101.22	101.15
Si	1.895	1.859	1.859	1.888	1.926	1.880	1.902	1.908
Ti	0.001	0.043	0.047	0.022	0.001	0.036	0.018	0.020
Al	0.069	0.072	0.067	0.062	0.055	0.082	0.064	0.067
Cr	0.012	0.012	0.013	0.011	0.014	0.017	0.017	0.016
Fe	0.361	0.377	0.367	0.373	0.655	0.570	0.511	0.499
Mn	0.003	0.010	0.008	0.015	0.001	0.013	0.011	0.013
Mg	0.864	0.852	0.836	0.839	1.048	0.901	1.274	1.245
Ca	0.852	0.824	0.846	0.836	0.338	0.530	0.240	0.256
Na	0.009	0.008	0.008	0.004	0.001	0.003	0.001	0.001
S	4.068	4.059	4.056	4.054	4.038	4.035	4.040	4.029
Al ^{IV}	.869	.072	.067	.062	.055	.082	.064	.067
Others	4.1	6.1	6.1	4.5	3.3	6.4	4.6	4.9
En	42	41	40	41	52	45	63	62
Wo	41	40	41	41	16	26	12	13
Fs	17	19	19	18	32	29	25	25

TABLE 3

14066, 36:

	1E	1C	1C	2	3	4	5
SiO ₂	50.61	51.43	51.46	51.10	51.10	52.04	52.05
TiO ₂	1.61	0.77	1.31	0.84	1.21	1.22	1.13
Al ₂ O ₃	0.57	0.66	0.71	1.04	1.12	0.97	1.10
Cr ₂ O ₃	0.13	0.19	0.17	0.21	0.19	0.17	0.22
FeO	9.95	19.52	19.68	19.37	19.50	19.29	19.38
MnO	0.22	0.38	0.18	0.37	0.32	0.32	0.28
MgO	16.46	23.42	23.38	22.38	24.66	24.59	24.31
CaO	21.30	4.21	3.81	3.40	2.15	2.11	2.24
Na ₂ O	0.19	0.05	0.16	0.02	0.03	0.01	0.03
Total	101.06	100.68	100.88	98.75	100.31	100.77	100.78
Si	1.887	1.923	1.918	1.927	1.906	1.913	1.914
Ti	0.047	0.021	0.035	0.023	0.033	0.033	0.031
Al	0.025	0.028	0.030	0.046	0.048	0.042	0.047
Cr	0.003	0.005	0.005	0.006	0.005	0.004	0.006
Fe	0.310	0.598	0.601	0.610	0.596	0.593	0.596
Mn	0.007	0.011	0.005	0.011	0.009	0.010	0.008
Mg	0.915	1.280	1.274	1.257	1.345	1.347	1.332
Ca	0.851	0.165	0.149	0.137	0.084	0.083	0.088
Na	0.014	0.004	0.011	0.001	0.002	0.001	0.002
Σ	4.059	4.040	4.033	4.023	4.033	4.029	4.028
Al ^{IV}	0.025	0.028	0.030	0.046	0.048	0.042	0.047
Others	4.0	2.7	3.8	3.6	4.1	4.7	4.1
En	44	62	63	63	66	66	66
Wo	41	8	7	7	4	4	4
Fs	15	30	30	30	30	30	30

TABLE 4

14305, 107:

	1C	1C	1E	2E	2E	2E	3I	3I	3I	3E
SiO ₂	52.25	52.29	52.21	51.47	51.26	52.21	51.06	51.17	50.73	50.38
TiO ₂	0.72	0.77	0.85	0.70	0.89	0.86	0.89	0.84	1.37	1.45
Al ₂ O ₃	0.72	0.70	0.76	0.79	0.95	0.86	0.71	1.84	1.63	1.67
Cr ₂ O ₃	0.21	0.25	0.24	0.26	0.27	0.24	0.21	0.63	0.61	0.39
FeO	21.71	21.97	21.60	22.29	20.52	21.64	22.10	17.05	20.74	11.87
MnO	0.36	0.34	0.35	0.35	0.27	0.34	0.34	0.35	0.25	0.20
MgO	20.60	20.97	19.54	20.29	22.81	20.43	19.99	20.34	19.36	14.45
CaO	3.85	3.67	3.92	4.05	2.22	4.31	3.83	6.36	4.89	17.96
Na ₂ O	0.06	0.05	0.05	0.06	0.03	0.04	0.03	0.04	0.22	0.20
Total	100.53	101.05	99.57	100.30	99.26	100.97	99.20	98.65	99.83	98.61
Si	1.966	1.946	1.968	1.951	1.912	1.945	1.942	1.926	1.914	1.919
Ti	0.020	0.021	0.024	0.019	0.025	0.024	0.025	0.024	0.039	0.041
Al	0.031	0.030	0.033	0.034	0.042	0.038	0.032	0.081	0.072	0.075
Cr	0.006	0.007	0.007	0.008	0.007	0.006	0.018	0.018	0.018	0.011
Fe	0.670	0.683	0.681	0.693	0.652	0.674	0.703	0.536	0.654	0.378
Mn	0.011	0.010	0.011	0.011	0.008	0.010	0.010	0.011	0.008	0.006
Mg	1.134	1.163	1.098	1.124	1.293	1.134	1.133	1.141	1.088	0.820
Ca	0.152	0.146	0.158	0.161	0.090	0.172	0.156	0.256	0.197	0.733
Na	0.004	0.003	0.004	0.004	0.002	0.003	0.002	0.002	0.016	0.015
Σ	3.997	4.014	3.988	4.009	4.037	3.009	4.013	4.000	4.009	4.002
ΣTet										
Al ^{IV}										
Others	3.0	2.9	3.4	3.1	3.6	3.5	3.1	6.0	6.9	6.8
En	58	58	57	57	63	57	57	59	56	42
Wo	8	7	8	8	4	9	8	13	10	38
Fs	26	35	35	35	33	34	35	28	34	20

TABLE 5

14307, 42:

	1	2	3	4C	4E	5	6	7
SiO ₂	50.28	52.26	53.04	52.55	50.34	52.57	50.05	51.80
TiO ₂	0.81	1.06	1.00	1.16	2.31	1.27	0.12	0.74
Al ₂ O ₃	4.55	1.14	1.04	1.42	2.49	0.98	5.43	1.05
Cr ₂ O ₃	0.26	0.25	0.28	0.32	0.56	0.26	0.18	0.27
FeO	18.07	18.12	19.22	18.00	8.85	18.36	17.10	16.95
MnO	0.27	0.27	0.29	0.27	0.18	0.27	0.09	0.28
MgO	23.47	23.77	23.38	23.46	15.88	23.43	22.55	23.64
CaO	1.82	2.07	1.80	2.07	17.59	1.98	1.69	1.81
Na ₂ O	0.04	0.04	0.03	0.04	0.21	0.02	0.04	0.04
Total	99.61	99.03	100.10	99.33	98.46	99.19	98.18	98.62
Si	1.856	1.940	1.953	1.942	1.893	1.949	1.889	1.985
Ti	0.022	0.029	0.027	0.032	0.065	0.035	0.003	0.020
Al	0.198	0.050	0.045	0.062	0.110	0.042	0.237	0.045
Cr	0.007	0.007	0.008	0.009	0.016	0.007	0.005	0.008
Fe	0.558	0.562	0.591	0.556	0.278	0.569	0.530	0.523
Mn	0.008	0.008	0.009	0.008	0.006	0.008	0.003	0.008
Mg	1.292	1.316	1.283	1.293	0.890	1.295	1.246	1.300
Ca	0.072	0.082	0.071	0.082	0.709	0.078	0.067	0.071
Na	0.002	0.003	0.002	0.003	0.015	0.001	0.003	0.003
Σ	4.019	4.002	3.992	3.990	3.985	3.989	3.987	3.968
IT _{Fe}								
Al _{IV}								
Others	10.6	4.3	4.0	5.2	9.8	4.1	11.8	3.8
En	67	67	66	67	47	66	68	69
Wo	4	4	4	4	38	4	4	4
Fs	29	29	30	29	15	30	28	27

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TABLE 6

14066, 10:

	1	2	3
SiO ₂	51.18	50.76	50.94
TiO ₂	1.38	1.31	1.40
Al ₂ O ₃	1.49	2.95	1.52
Cr ₂ O ₃	0.51	0.49	0.50
FeO	11.02	11.04	10.74
MnO	0.19	0.20	0.20
MgO	14.90	14.97	15.00
CaO	18.20	18.30	18.49
Na ₂ O	0.16	0.18	0.18
Total	99.07	100.24	99.00
Si	1.918	1.893	1.911
Ti	0.039	0.036	0.040
	0.067	0.129	0.068
	0.015	0.014	0.015
Fe	0.352	0.344	0.343
Mn	0.006	0.006	0.006
Mg	0.849	0.832	0.855
Ca	0.745	0.731	0.758
Na	0.012	0.013	0.013
Σ	4.006	4.003	4.013

TABLE 7

14066, 35:

52.19	52.14
1.59	0.79
1.87	0.76
0.28	0.28
20.35	22.33
0.34	0.27
19.07	19.56
4.59	3.69
0.05	0.09
100.37	99.95
1.943	1.964
0.044	0.022
0.082	0.033
0.009	0.008
0.633	0.703
0.010	0.008
1.058	1.098
0.183	0.149
0.004	0.006
3.969	3.995

TABLE 8

14066, 36:

52.35	51.51	51.79
1.17	1.11	0.92
1.16	1.06	0.94
0.28	0.25	0.32
18.83	19.67	19.18
0.28	0.28	0.30
23.00	22.38	22.97
2.26	2.10	1.93
0.01	0.02	0.01
99.37	98.41	98.39
1.930	1.951	1.964
0.033	0.031	0.026
0.051	0.047	0.042
0.008	0.007	0.009
0.592	0.591	0.608
0.009	0.009	0.009
1.289	1.264	1.242
0.091	0.085	0.078
0.001	0.001	0.001
4.006	3.990	3.983

TABLE 9

14082, 5:

	1	2	3	4
SiO ₂	49.70	50.33	50.42	50.92
TiO ₂	1.73	0.76	1.42	0.71
Al ₂ O ₃	2.25	0.94	1.92	0.95
FeO	13.02	23.55	12.96	23.66
MnO	0.01	0.02	-	0.01
MgO	15.00	17.63	15.00	18.38
CaO	16.98	5.03	16.72	4.64
Na ₂ O	0.17	0.09	0.16	0.07
Total	98.89	98.37	98.62	99.40
Si	1.891	1.949	1.918	1.947
Ti	0.049	0.022	0.040	0.020
Al	0.101	0.042	0.086	0.043
Fe	0.414	0.762	0.412	0.756
Mn	0.001	0.001	-	-
Mg	0.851	1.017	0.851	1.047
Ca	0.692	0.209	0.681	0.190
Na	0.013	0.006	0.012	0.005
E	4.015	4.011	4.003	4.013
En	43	51	43	52
Wo	35	10	34	10
Fs	22	39	23	38

TABLE 10

14082, 6:

	1	2
SiO ₂	51.46	50.02
TiO ₂	0.85	1.23
Al ₂ O ₃	0.83	1.06
FeO	21.40	17.37
MnO	-	-
MgO	22.34	12.31
CaO	1.29	17.17
Na ₂ O	0.01	0.11
Total	98.21	99.30
Si	1.950	1.934
Ti	0.024	0.035
Al	0.037	0.048
Fe	0.678	0.561
Mn	-	-
Mg	1.262	0.709
Ca	0.052	0.711
Na	0.001	0.008
E	4.006	4.010
En	63	35
Wo	2	36
Fs	35	29

TABLE 11

14307, 42:

	1	2
SiO ₂	50.87	49.14
TiO ₂	1.33	1.84
Al ₂ O ₃	1.35	2.02
FeO	24.55	21.22
MnO	0.02	-
MgO	15.50	11.52
CaO	5.46	15.15
Na ₂ O	0.04	0.12
Total	99.17	101.05
Si	1.960	1.890
Ti	0.038	0.053
Al	0.061	0.091
Fe	0.791	0.682
Mn	-	-
Mg	0.890	0.661
Ca	0.225	0.624
Na	0.003	0.009
E	3.972	4.014
En	45	33
Wo	11	31
Fs	44	36

TABLE 12

14066, 10:

	1E	1C	2E	2I	2C	3E	3C
SiO ₂	52.54	52.78	53.89	53.17	51.84	52.79	52.98
TiO ₂	1.02	1.09	0.80	0.84	0.82	0.92	0.89
Al ₂ O ₃	1.01	1.32	0.98	1.12	2.27	1.07	1.08
Cr ₂ O ₃	0.40	0.45	0.33	0.34	0.36	0.37	0.38
FeO	15.42	15.02	14.79	14.75	14.53	15.57	14.74
MnO	0.24	0.24	0.21	0.22	0.22	0.24	0.24
MgO	25.95	26.65	26.71	26.63	26.36	25.68	25.87
CaO	2.03	1.84	1.92	1.86	2.08	2.18	2.14
Na ₂ O	0.06	0.05	0.04	0.04	0.06	0.05	0.05
Total	98.71	99.49	99.71	99.02	98.58	98.91	98.41
Si	1.934	1.923	1.952	1.941	1.890	1.940	1.948
Ti	0.028	0.030	0.021	0.023	0.023	0.025	0.024
Al	0.044	0.056	0.042	0.048	0.099	0.046	0.047
Cr	0.011	0.013	0.009	0.009	0.010	0.010	0.011
Fe	0.475	0.458	0.448	0.450	0.452	0.478	0.453
Mn	0.007	0.007	0.006	0.007	0.007	0.007	0.007
Mg	1.424	1.447	1.442	1.449	1.461	1.406	1.418
Ca	0.080	0.071	0.074	0.073	0.083	0.085	0.084
Na	0.004	0.004	0.003	0.003	0.004	0.004	0.003
Σ	4.011	4.013	4.001	4.007	4.033	4.007	3.999
En	71	72					
Wo	4	3					
Fs	25	25					

TABLE 13

14066, 36:

	1	2	3E	3C	4E	4C	5
SiO ₂	51.88	50.55	52.49	52.64	52.67	52.56	52.94
TiO ₂	1.33	1.93	0.93	0.93	0.80	0.91	1.01
Al ₂ O ₃	1.61	1.63	0.96	1.05	0.74	0.86	1.14
Cr ₂ O ₃	0.26	0.34	0.21	0.28	0.28	0.29	0.28
FeO	21.30	11.22	20.63	21.19	19.62	19.48	19.00
MnO	0.33	0.24	0.32	0.24	0.28	0.29	0.27
MgO	21.90	14.30	21.29	21.02	22.82	23.31	23.28
CaO	1.91	18.60	2.16	1.93	1.94	1.73	1.64
Na ₂ O	0.01	0.12	0.02	0.14	0.02	0.01	0.01
Total	100.58	98.97	99.04	99.46	99.22	99.48	99.61
Si	1.924	1.902	1.955	1.956	1.977	1.966	1.956
Ti	0.037	0.055	0.026	0.026	0.022	0.025	0.028
Al	0.070	0.073	0.043	0.047	0.032	0.038	0.049
Cr	0.007	0.010	0.006	0.008	0.008	0.008	0.008
Fe	0.660	0.360	0.655	0.671	0.600	0.593	0.587
Mn	0.010	0.008	0.010	0.007	0.009	0.009	0.008
Mg	1.211	0.818	1.205	1.187	1.249	1.272	1.282
Ca	0.075	0.765	0.088	0.078	0.078	0.069	0.065
Na	0.001	0.009	0.001	0.010	0.001	0.001	0.001
Σ	3.999	4.004	3.993	3.994	3.980	3.985	3.987
En	60	40					
Wo	4	38					
Fs	36	22					

TABLE 14

14305, 107:

	1E	1C	2	3	4	5
SiO ₂	53.11	52.89	51.42	52.84	51.41	51.34
TiO ₂	0.44	0.50	1.01	0.75	1.58	1.74
Al ₂ O ₃	1.09	1.06	1.23	0.71	1.68	1.82
Cr ₂ O ₃	0.54	0.51	0.22	0.28	0.49	0.57
FeO	18.29	18.81	21.64	20.91	11.58	11.00
MnO	0.36	0.35	0.22	0.35	0.20	0.21
MgO	19.76	19.75	18.50	19.72	14.09	14.50
CaO	6.42	6.04	6.16	5.41	17.26	19.32
Na ₂ O	0.01	0.03	0.49	0.05	0.17	0.13
Total	100.06	99.98	100.93	101.06	98.50	100.57

TABLE 15

14305, 102:

	1E	1C	2E	2C	3
	49.70	50.50	53.93	53.35	50.38
	1.71	1.62	0.32	0.48	1.59
	1.84	1.95	0.96	1.58	1.54
	0.42	0.50	0.80	0.87	0.26
	17.12	15.24	16.34	16.38	16.03
	0.30	0.28	0.33	0.30	0.30
	13.39	14.37	23.20	24.17	12.75
	15.48	15.48	4.58	3.80	17.15
	0.10	0.19	0.01	0.01	0.11
	100.11	100.19	100.51	100.97	100.15

TABLE 16

14066, 51:

	1	2	3
SiO ₂	52.29	52.62	52.41
TiO ₂	0.61	0.60	0.64
Al ₂ O ₃	0.60	0.56	0.64
Cr ₂ O ₃	0.19	0.20	0.32
FeO	22.68	21.41	14.84
MnO	0.39	0.40	0.34
MgO	19.28	18.54	17.93
CaO	3.28	5.48	12.05
Na ₂ O	0.05	0.01	0.02
Total	99.40	99.85	99.22

TABLE 17

14082, 5:

14082, 6:

	1	2	3	1	2	3
TiO ₂	54.32	54.83	54.63	54.93	54.89	54.19
Al ₂ O ₃	0.07	0.05	0.08	0.07	0.06	0.10
Cr ₂ O ₃	0.40	0.43	0.55	0.51	0.51	0.31
FeO	41.06	40.95	40.92	38.31	39.05	39.63
MnO	0.38	0.36	0.39	0.39	0.38	0.32
MgO	3.71	4.06	4.12	5.39	5.19	4.37
Total	99.97	100.97	100.71	99.62	100.09	98.94

TABLE 18

14307, 42:

	1	2	3
TiO ₂	55.53	54.29	54.57
Al ₂ O ₃	0.22	0.48	0.12
Cr ₂ O ₃	0.79	0.33	0.33
FeO	37.67	37.45	37.91
MnO	0.38	0.31	0.32
MgO	6.28	6.03	6.07
Total	100.90	98.93	99.33

TABLE 19

14305, 102:

	1	2
TiO ₂	54.46	54.84
Al ₂ O ₃	0.01	0.02
Cr ₂ O ₃	0.43	0.43
FeO	39.51	39.54
MnO	0.33	0.31
MgO	5.03	5.16
Total	99.77	100.31

TABLE 20

14305, 107:

	1E	1C	2E	2I	2C	3	4C	4I	4E	5	6
SiO ₂	45.18	44.71	44.29	44.58	44.78	44.56	44.67	45.23	45.15	43.54	44.03
TiO ₂	0.07	0.06	0.05	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.03
Al ₂ O ₃	36.14	36.26	36.00	35.70	35.79	35.87	35.37	34.05	33.90	35.46	36.07
FeO	0.14	0.09	0.24	0.17	0.12	0.25	0.23	0.19	0.22	0.07	0.10
MnO	-	-	-	-	0.01	-	-	-	0.01	-	-
MgO	0.01	-	0.01	0.01	0.01	0.02	0.01	0.08	0.14	-	-
CaO	17.76	18.47	18.42	18.60	18.54	18.34	17.65	17.74	17.65	18.26	18.03
Na ₂ O	1.11	0.69	0.75	0.65	0.65	0.62	0.85	0.84	1.03	0.61	0.74
K ₂ O	0.05	0.03	0.05	0.05	0.03	0.06	0.08	0.07	0.13	0.04	0.01
Total	100.51	100.33	99.83	99.82	99.99	99.77	98.92	98.26	98.29	98.04	99.04
Si	2.069	2.053	2.047	2.060	2.064	2.058	2.078	2.117	2.115	2.047	2.035
Ti	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	-	0.001	0.001
Al	1.950	1.962	1.961	1.944	1.944	1.953	1.939	1.878	1.872	1.965	1.988
Fe	0.005	0.003	0.009	0.006	0.004	0.009	0.009	0.007	0.008	0.002	0.004
Mn	-	-	-	-	0.001	-	-	-	-	-	-
Mg	0.001	-	0.001	0.001	0.001	0.001	0.001	0.005	0.010	-	-
Ca	0.871	0.908	0.912	0.921	0.915	0.907	0.880	0.889	0.886	0.920	0.903
Na	0.099	0.061	0.067	0.058	0.058	0.056	0.077	0.076	0.093	0.056	0.067
K	0.003	0.002	0.003	0.003	0.002	0.003	0.004	0.004	0.008	0.002	-
Σ	5.004	4.994	5.004	4.996	4.992	4.992	4.991	4.982	4.997	4.997	5.002

TABLE 21

	1	2C	2E
SiO ₂	44.28	44.74	44.14
TiO ₂	0.02	0.04	0.04
Al ₂ O ₃	35.81	35.49	36.14
FeO 0.09	0.09	0.14	0.10
MnO	-	-	-
MgO	-	-	-
CaO	17.76		
Na ₂ O	1.06	0.82	0.87
K ₂ O	0.08	0.06	0.05
Total	99.12	99.37	99.34
Si	2.058	2.073	2.046
Ti	-	0.001	0.001
Al	1.961	1.932	1.969
Fe	0.003	0.005	0.003
Mn	-	-	-
Mg	-	-	-
Ca	0.884	0.906	0.903
Na	0.095	0.075	0.079
K	0.004	0.003	0.003
Σ	5.010	4.998	5.008

TABLE 22

	1E	1C	2E	2C	3
	45.67	45.56	44.71	44.60	45.59
	0.08	0.14	0.08	0.08	0.06
	35.69	35.34	35.75	35.84	35.50
	0.18	0.19	0.22	0.19	0.20
	0.01	0.01	0.01	0.01	0.01
	0.02	-	0.02	0.01	0.01
	1.25	1.11	1.09	0.88	1.41
	0.10	0.15	0.10	0.07	0.12
	99.87	99.61	99.24	99.23	99.56

TABLE 23

14066, 35:

	1E	1I	1I	1C	2E	2C	3E	3C	4	5
SiO ₂	45.61	45.84	45.14	45.23	45.60	45.75	45.10	45.78	45.49	44.56
TiO ₂	0.31	0.09	0.10	0.08	0.08	0.08	0.09	0.07	0.07	0.03
Al ₂ O ₃	34.72	34.93	35.21	35.18	34.84	34.57	35.19	34.68	35.04	36.09
FeO	0.26	0.14	0.17	0.13	0.31	0.25	0.33	0.28	0.29	0.16
MnO	0.01	0.01	-	-	0.01	0.01	-	-	-	0.02
MgO	-	-	-	-	0.01	-	0.01	0.02	0.01	-
CaO	17.13	16.85	17.22	17.19	17.03	17.23	17.31	18.20	17.47	17.14
Na ₂ O	1.11	1.28	1.06	1.02	1.24	1.17	1.06	0.70	1.00	0.99
K ₂ O	0.11	0.11	0.13	0.14	0.12	0.11	0.09	0.05	0.12	0.12
Total	99.29	99.28	99.04	99.00	99.26	99.20	99.22	99.82	99.53	99.14
Si	2.111	2.118	2.094	2.098	2.111	2.097	2.091	2.111	2.102	2.066
Ti	0.011	0.003	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.001
Al	1.891	1.902	1.925	1.923	1.902	1.910	1.923	1.885	1.909	1.972
Fe	0.010	0.005	0.006	0.005	0.012	0.009	0.012	0.011	0.011	0.006
Mn	-	-	-	-	-	-	-	-	-	-
Mg	-	-	-	-	-	-	0.001	0.001	0.001	-
Ca	0.853	0.834	0.856	0.856	0.854	0.865	0.860	0.899	0.865	0.851
Na	0.100	0.115	0.095	0.092	0.111	0.106	0.095	0.062	0.089	0.089
K	0.006	0.007	0.007	0.008	0.007	0.007	0.005	0.003	0.007	0.007
Σ	4.985	4.987	4.990	4.986	4.993	5.001	4.994	4.976	4.989	4.994

TABLE 24

14305, 102:

	1	2	3	4E	4I	4C	1E	1C	2E	2C
SiO ₂	43.80	43.91	45.64	46.64	46.78	46.47	45.47	45.52	49.84	47.11
TiO ₂	0.03	0.02	0.02	0.03	0.03	0.05	0.12	0.09	0.09	0.11
Al ₂ O ₃	36.09	35.47	35.19	33.91	33.84	34.05	35.90	34.67	31.96	33.78
FeO	0.15	0.13	0.16	0.11	0.11	0.11	0.15	0.21	0.12	0.22
MnO	-	0.01	-	-	-	-	0.01	-	-	0.01
MgO	0.03	0.02	0.05	-	-	0.02	0.02	0.03	0.03	-
CaO	18.28	18.34	16.91	16.06	16.37	16.33	16.81	17.08	14.62	16.01
Na ₂ O	0.74	0.80	0.92	2.10	1.90	1.76	1.22	1.20	2.29	1.65
K ₂ O	0.03	-	0.26	0.17	0.13	0.25	0.14	0.11	0.31	0.21
Total	99.18	98.72	99.16	99.05	99.19	99.06	99.88	98.97	99.28	99.12

TABLE 25

TABLE 26 Average Compositions of Apollo 14 poikilitic rocks

	14305, 107	14066, 36	14066, 51	14305, 42
SiO ₂	51.86	46.68	51.09	46.90
TiO ₂	1.07	0.37	0.47	1.45
Al ₂ O ₃	25.73	27.31	23.48	19.67
Cr ₂ O ₃	0.06	0.07	0.06	0.16
FeO	4.21	5.75	7.05	8.56
MnO	0.05	0.09	0.11	0.13
MgO	3.61	5.94	6.09	10.78
CaO	13.60	12.93	10.85	11.43
Na ₂ O	0.77	0.79	0.73	0.80
Total	100.99	100.00	100.00	100.00

Averages computed from defocussed beam analyses of individual clasts.

References Cited

- Albee, A.L., A.J. Gancarz and A.A. Chodos (1973). Proc. Fourth Lunar Sci. Conf. vol. 1, 569-95.
- Ashwal, L.D. (1975). Proc. Sixth Lunar Sci. Conf. vol. 1, 221-230.
- Bence, A.E., J.J. Papike, S. Sueno and J.W. Delano (1973). Proc. Fourth Lunar Sci. Conf. vol. 1, 597-611.
- Crawford, M.L. and L.S. Hollister (1974). Proc. Fifth Lunar Sci. Conf. vol. 1, 399-419.
- Duncan, A.K., R.A.F. Grieve and D.F. Weill (1975). Geochim. Cosmochim. Acta, vol. 39, 265-73.
- Grieve, R.A.F. (1975). Bull. Geol. Soc. Am. vol. 86, 1617-29.
- Grieve, R.A.F., A.G. Plant and M.R. Dence (1974). Proc. Fifth Lunar Sci. Conf. vol. 1, 261-74.
- Grieve, R.A.F., G.A. McKay, H.D. Smith and D.F. Weill (1975). Geochim. Cosmochim. Acta., vol. 39, 229-45.
- Hodges, F.N., I. Kushiro and M.G. Seitz (1973). Lunar Sci. N., 371-73.
- Hollister, L.S. (1973). Proc. Fourth Lunar Sci. Conf. vol. 1, 633-41.
- Irving, A.J. (1975). Proc. Sixth Lunar Sci. Conf. vol. 1, 363-94.
- James, O.B. (1976). Lunar Sci. VII. 420-22.
- McCallum, S, E.A. Mathez, F.P. Okamura and S. Ghose (1974). Proc. Fifth Lunar Sci. Conf. vol. 1, 287-302.
- Ridley, W.I. (1974). Trans. Roy. Soc. London (in press).
- Roedder, E. and P. Weiblen (1974). Proc. Fifth Lunar Sci. Conf. vol. 1, 303-18.
- Ryder, E. and J.F. Bower (1976). In Interdisciplinary studies by the Imbrium Consortium, 22-37.
- Schaeffer, J. and L.S. Hollister (1975). Lunar Sci. VI. 706-7.
- Simonds, C.H. (1975). Proc. Sixth Lunar Sci. Conf. vol. 1, 641-72.
- Simonds, C.H., J.L. Warner and W.C. Phinney (1973). Proc. Fourth Lunar Sci. Conf. vol. 1, 613-32.
- Simonds, C.H., J.L. Warner and W.C. Phinney (1976). Lunar Sci. VII. 812-14.
- Steele, I.M. and J.V. (1973). Proc. Fourth Lunar Sci. Conf. vol. 1, 519-36.
- Wager, L.R. (1961). Geol. Mag., vol. 98, 353-66.
- Walker, D., J. Longhi, T.L. Grove, E. Stolper and J. Hays (1973). Proc. Fourth Lunar Sci. Conf. vol. 1, 1013-32.

PETROLOGY OF LUNAR ROCKS AND IMPLICATION TO LUNAR EVOLUTION¹

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INTRODUCTION

The lunar surface can be divided into three major lithologic units: regolith or comminuted rock, mare bedrock, and terra bedrock. Each of these units can be recognized by distinctive physical and chemical properties, the most obvious of which is the brightness or albedo of the individual units. In general, the terra regions are uniformly much brighter than the mare.

Wherever sampled, the mare basalts, which partially fill large impact basins, are overlain by a veneer of impact-comminuted rock. A physically similar, but chemically different, thicker veneer covers the terra regions. As a consequence of this surface blanket, no in situ rock sample has ever been returned from the Moon. Despite this, it has been possible to collect samples of local bedrock from both the mare and terra regions, because small scale meteorite impact penetrated the regolith, ejecting bedrock to the surface.

The geological aspects of the Apollo program were designed so that maximum sample coverage of major geologic units could be achieved within the framework of a limited number of missions. This goal was achieved by the sampling of four large maria (Mare Tranquillitatis, Oceanus Procellarum, Palus Putredinus, Mare Serenitatis) and four major terra units (Fra Mauro, Apennine Mountains, Cayley-Descartes Highlands, Taurus-Littrow Highlands). Additional coverage was possible through two Russian Luna missions, which sampled Mare Fecunditatis and Apollonius Mountains; extrapolation of local chemical data to a more regional scale was achieved through chemical data obtained from the orbiting command modules on Apollo 15 and 16.

Chemically and petrologically the lunar samples held many surprises and properties beyond our terrestrial experience. Probably one of the most important discoveries was the simple observation that the Apollo 11 basalts had textures similar

¹ Contribution No. 2237 from Lamont-Doherty Geological Observatory.

to terrestrial basalts, and had crystallized from silicate liquids. Clearly the Moon has not always been a cold planet. As data from further missions accumulated, it became evident that the Moon was a dynamic, hot planet in its youthful stages. In addition, its overall chemical composition is distinctly different from the Earth; silicate liquids produced within the Moon are uniquely lunar in composition, and the conditions under which lunar magmas originated and crystallized were alien to the terrestrial environment.

In order to understand the petrogenesis of the Moon, it is best to present the broad picture that has emerged since 1969, and later to follow up with more specific evidence. Although many important petrogenetic questions remain, the first-order evolutionary sequence has generally been accepted.

The Moon accreted homogeneously at ~ 4.65 AE in a short time period (< 100 yr) with the storing of enough accretionary energy to cause melting of the outer few hundred kilometers. Cooling of the molten outer shell occurred during a period of high meteorite flux, and the cooling crust was continually broken and stirred into the molten interior. Eventually the lithosphere thickened and became rigid enough to withstand large meteorite bombardments, and the underlying molten zone cooled quiescently and underwent fractional crystallization. Gravity sinking of high density ferromagnesian minerals (pyroxene, olivine, ilmenite) relative to lighter plagioclase caused a chemical/mineralogical layering into an ultrabasic pyroxenitic mantle and a plagioclase-rich crust. The rigid crust was impacted by large meteorites, which lead to the excavation of the large mare basins between 4.6 AE and 3.9 AE. At ~ 3.9 AE a decrease in meteorite flux occurred, although by this time the lunar surface was saturated with 50 km diameter craters.

Internal heat sources (K, U, Th) were concentrated towards the surface between 4.6 AE and 3.9 AE, so that partial melting of the lunar upper mantle occurred between 3.8 AE and 3.1 AE, generating the mare basalts. These magmas ascended into the large mare basins, presumably because these were regions of crustal weakness. There seems to be no temporal relationship between mare basin formation and mare basalt genesis. Gradual thickening of the lunar lithosphere, as radioactive heat generation failed to match surface heat loss, depressed the zone of partial melting deeper into the lunar mantle. At ~ 3.1 AE the lithosphere was too thick to allow ascent of large volumes of mare basalt to the surface, and surface activity essentially ceased.

At present the Moon is not a cold, dead planet, but relative to the Earth it is in a condition of extreme quiescence. Moonquakes at depths of 800–1000 km suggest this may represent the base of the lunar lithosphere; heat flow calculations indicate a partially molten zone may still be present within the lunar asthenosphere; seismic velocity data suggest that the Moon may have a molten core equivalent to approximately 2% of its volume; lunar transient events identify contemporary surface activity on the Moon.

In summary, the three most important dynamic processes operative during the initial 1.6 AE of lunar history were external impact bombardment, internal fractional crystallization and internal partial melting. The latter process is best exemplified by the mare basalts, which fortunately erupted after the rapid decrease in meteorite

flux. They have therefore retained original textures and chemistry and are texturally similar, but are chemically unlike terrestrial basalts.

In contrast, the terra rocks are much more complex, reflecting the period between 4.6 AE and 3.9 AE, in which the lunar crust was continuously being fragmented, remelted, metamorphosed, mixed, and contaminated by large impacting meteorites. Most of the terra rocks are texturally complex, impact breccias or impact-produced melts, but a rare few are probably of pristine igneous origin derived from deep crustal levels. Studies of terra rocks are essentially studies of impact processes. These studies are fascinating, but the ultimate aim is to look behind this complicated curtain and evaluate the original stratigraphy of the lunar crust.

In the following sections, the petrochemistry of lunar rocks (mare basalts, terra assemblages, regoliths) are reviewed in the context of the generalized evolutionary framework already outlined. Mare and terra assemblages are treated separately because they form distinct temporal and chemical units.

Much lunar literature may be found within the impressive 15 volumes of the Proceedings of the Annual Lunar Science Conferences. Recent reviews (Taylor 1975) present a timely precis of the wealth of data amassed since 1969.

MARE BASALTS

Major Element Composition

Three major groups of mare basalts have been recognized; representatives of each are shown in Table 1. Titanium-rich basalts with 11–13% TiO_2 and 9% Al_2O_3

Table 1 Major element composition of mare samples^a

	b	c	d	e	f	g	h	i	j
SiO_2	40.69	39.04	46.13	44.59	45.07	47.81	43.97	37.64	41.27
TiO_2	11.92	11.32	3.35	2.88	4.62	1.77	2.31	13.45	10.17
Al_2O_3	7.78	9.51	9.95	8.02	9.96	8.87	8.43	8.20	9.75
Cr_2O_3	—	—	0.46	0.55	0.26	—	—	0.57	0.27
FeO	19.49	19.40	20.70	22.03	20.25	19.97	22.58	18.78	18.24
MnO	0.28	0.27	0.28	0.29	0.28	0.28	0.33	0.28	0.29
MgO	7.51	7.73	8.07	12.66	7.21	9.01	11.14	9.49	6.84
CaO	10.76	11.28	10.89	9.05	11.45	10.32	9.40	10.29	12.30
Na_2O	0.51	0.36	0.26	0.20	0.28	0.28	0.21	0.40	0.44
K_2O	0.30	0.05	0.07	0.07	0.08	0.03	0.03	0.05	0.09

^a All analyses by X-ray fluorescence (XRF).

^b Apollo 11: high-K ilmenite basalt 10017 (Compston et al 1970).

^c Apollo 11: low-K ilmenite basalt 10045 (Compston et al 1970).

^d Apollo 12: pigeonite basalt 12052 (Compston et al 1971).

^e Apollo 12: olivine basalt 12004 (Compston et al 1971).

^f Apollo 12: ilmenite basalt 12051 (Compston et al 1971).

^g Apollo 15: pyroxene-phyric basalt 15058 (Rhodes & Hubbard 1973).

^h Apollo 15: olivine-phyric basalt 15016 (Rhodes & Hubbard 1973).

ⁱ Apollo 17: olivine porphyritic ilmenite basalt 75075 (Rhodes et al 1974).

^j Apollo 17: "Apollo 11 low-K type" 75055 (Rhodes et al 1974).

were collected from Mare Tranquillitatis and Serenitatis, titanium-poor basalts with 2–4% TiO_2 and 9% Al_2O_3 occur in Oceanus Procellarum and Palus Putredinus, and aluminous basalts with 11–14% Al_2O_3 occur in Mare Fecunditatis and as rare samples at other sites. However, this does not imply that these maria are filled by basalts of these specific compositions, since spectral and photogeologic analysis (Bryan & Adams 1973, Howard et al 1973, Pieters et al 1975) indicate a variety of basaltic types in each mare. Figures 1 and 2 indicate that basalts from each mare can be distinguished by simple binary plots (Rhodes & Hubbard 1973, Rhodes et al 1974), and within each mare a number of subgroups, each with slightly different chemistry, may be recognized.

This leads to a classification of mare basalts based upon a combination of major element chemistry and mineralogy, as illustrated in Table 2. Textural classifications are also possible (Warner 1971) and are useful for cooling rate studies, but they have less petrogenetic significance.

At the Apollo 12, 15, and 17 sites, both quartz- and olivine-normative basalts have been analyzed (James & Wright 1972, Rhodes & Hubbard 1973, Shih et al 1975), but the relationships between each type are complex. For instance, at the Apollo 12 site the olivine- and quartz-normative basalts may be related by low pressure fractional crystallization (James & Wright 1972), but not at the Apollo 15 or 17 sites. In the latter cases, the two basaltic magmas are related to two different parental magmas (Rhodes & Hubbard 1973, Shih et al 1975).

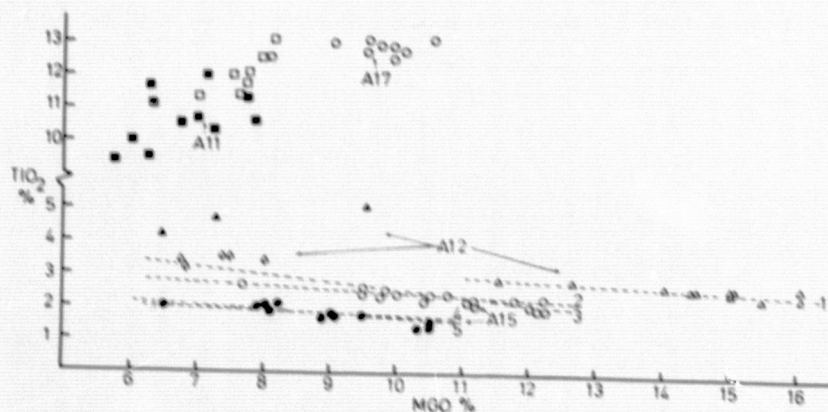


Figure 1. TiO_2 -MgO relations for mare basalts. Each of the sampled mare may be separated using this diagram. Note the wide range in MgO content of Apollo 12 and 15 basalts. Lines 1, 2, and 4 are olivine fractionation control lines; lines 3 and 5 are pigeonite fractionation control lines. Apollo 11 (A11): high-K type (open squares) and low-K type (filled squares). Apollo 17 (A17): (open polygons). Apollo 12 (A12): ilmenite basalts (filled triangles), olivine basalts (open triangles), and pigeonite basalts (dashed triangles). Apollo 15 (A15): olivine-normative basalts (open circles) and quartz-normative basalts (filled circles). Data are from Compston et al (1970, 1971), Rose et al (1972, 1973), Rhodes & Hubbard (1973), Rhodes et al (1974).

Low pressure fractional crystallization is a viable method of producing within-group variation at nearly all mare sites, as demonstrated in Table 3. Only in some cases has testing of this process included trace element budgets (Shih et al 1975). Because mare magmas are about three times less viscous than terrestrial basalts (Weill et al 1970), gravitation settling should be an efficient process. However, most of the textural and mineral chemical features can be accounted for by a one-stage cooling history (Dowty et al 1974a) from liquids erupted essentially crystal-free. Hence the major fractional crystallization must occur during the cooling of lava at the lunar surface. Most fractionation schemes underscore the minor role of plagioclase in this process, indicating that the ubiquitous europium anomaly (see below) cannot be produced by fractionation of large volumes of plagioclase.

The spectrum of basalts observed in large hand specimens has been expanded by studies involving smaller and more numerous lithic fragments and glasses found in the lunar soil. Glass studies involve the recognition of preferred chemical compositions among impact-produced glasses (Reid et al 1972, Reid et al 1973c), as shown in Table 4. Green glass from Palus Putredinus and orange glass from the Littrow valley have aroused much interest because of their unusual compositions (Table 3) and remarkable chemical homogeneity (in contrast to the heterogeneous impact glass). Although there is no consensus of opinion on their origin, they are most likely volcanic glasses (Cadenhead 1973, Prinz et al 1973a, Reid et al 1973a).

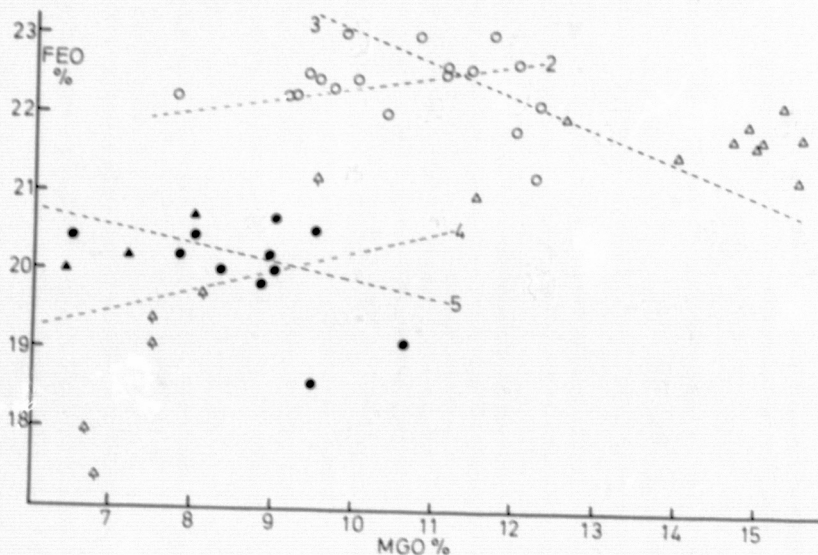


Figure 2 FeO-MgO relations for mare basalts to illustrate pigeonite control. Lines 2 and 4 are olivine control lines; lines 3 and 5 are pigeonite control lines. Symbols and data sources as in Figure 1.

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Table 2 Classifications of mare basalts

Mission	Chemical/mineralogical classification	Reference	Textural classification	Reference
Apollo 11	High-K ilmenite basalt =	a, b, c	Type A, fine-grained	
	Group 1 basalt ($K_2O > 0.11\%$)	d	vesicular basalt =	
	Low-K ilmenite basalt =	a, b	intersertal ilmenite basalt	b, e
	Group 2 basalt ($K_2O < 0.11\%$)	d	Type B, medium-grained, vuggy basalt = ophitic ilmenite basalt	b, e
	No systematic relationship between classifications			
Apollo 12	Olivine basalt ($MgO > 11.5\%$)	b	Porphyritic basalt	e
	Pigeonite basalt ($MgO < 8.5\%$)	b	Ophitic basalt	e
	Ilmenite basalt ($TiO_2 > 4\%$)	b		
	Feldspathic basalt ($Al_2O_3 > 11.4\%$)	b		
	(Less complete classification given by: f, g, h) No systematic relationship between classifications			
Apollo 15	Olivine-normative basalt ($SiO_2 < 46\%$)	i	Porphyritic clinopyroxene basalt = pyroxene-phyric basalt = mare basalt I	j k l
	Quartz-normative basalt ($SiO_2 > 47\%$)	i	Porphyritic clinopyroxene vitrophyres = pyroxene-phyric basalt = mare basalt II	j k l
			Porphyritic olivine basalt = olivine-phyric basalt = mare basalt III	j k l

Table 3 Low-pressure fractional crystallization schemes for mare basalts

Site	Basalt group	Minerals removed	Relationship to natural sequence	Reference
Apollo 11	Low-K ilmenite basalts	Minor olivine and minor armalcolite	Consistent	a, b
	No relationship between low-K and high-K ilmenite basalts.			
Apollo 12	Olivine basalts	Up to 17% olivine, minor chrome-spinel. Rarely 5% pigeonite	Consistent	a
	Pigeonite basalts	6-10% pigeonite, minor olivine and chrome-spinel	Consistent	a
	Olivine basalts to pigeonite basalts	Up to 20% olivine, up to 6% pigeonite, minor chrome-spinel	Consistent	a
	Ilmenite basalts	21% olivine, 12-16% pyroxene, 8% plagioclase, 3% ilmenite	Inconsistent	a
Apollo 15	Olivine basalts	Up to 14% olivine (Fo 73), 1% spinel	Consistent	c
	Pigeonite	Up to 14% pigeonite, minor olivine (Fo 70), and spinel	Consistent	c
	Olivine basalt to pigeonite basalt	Olivine, pigeonite, plagioclase, spinel	Inconsistent	c
Apollo 17	All	Minor olivine, armalcolite	Consistent	b

* James & Wright (1972)

* Longhi et al (1974)

* Rhodes & Hubbard (1973)

formed either by lava fountaining or by meteorite impact into a molten lava lake (Roedder & Weiblen 1973). They are an enigma, chemically unlike the local mare basalts with which they are closely associated.

Comparison of the mare surface basalts with orbital X-ray fluorescence (Adler et al 1972a, b) and gamma-ray spectrographic data (Metzger et al 1973, 1974) allows a more regional view of the composition of mare surfaces (Figure 3). In general, the mare surfaces have higher Al/Si ratios than the mare basalts. This anomaly is conveniently explained—the orbital data reflect the composition of mare regoliths, i.e. a mixture of mare basalt fragments and aluminous terra rocks (Wood et al

Table 4 Mare basalt compositions deduced from glass studies

	a	b	c	d	e	f
SiO ₂	45.62(0.55)	38.63(0.33)	48.22	40.2	45.48	44.55
TiO ₂	0.41(0.04)	8.96(0.47)	1.09	7.2	2.77	3.79
Al ₂ O ₃	7.74(0.39)	5.87(0.36)	12.93	13.2	10.86	11.77
Cr ₂ O ₃	0.44(0.04)	0.55(0.03)	0.37	—	—	0.26
FeO	19.51(0.68)	22.00(0.32)	15.55	16.5	18.14	18.83
MgO	17.65(0.62)	14.79(1.15)	8.69	8.5	11.21	8.84
MnO	—	—	—	—	—	—
CaO	8.33(0.48)	7.31(0.40)	12.38	12.0	9.56	10.46
Na ₂ O	0.12(0.05)	0.37(0.13)	0.45	0.3	0.39	0.34
K ₂ O	0.02(0.02)	0.08(0.02)	0.02	0.10	0.32	0.13
Site	Apollo 15	Apollo 17	Apollo 17	Apollo 11	Apollo 14	Apollo 15

^a Green glass in soil 15021.

^b Orange glass in soil 74240 (Reid et al 1973b).

^c Preferred composition in soil 74240 (Reid et al 1973b). Similar compositions occur in Apollo 15 soil.

^d "Tranquillitatis-type" composition in Apollo 11 soil. Similar compositions occur in soil at Apollo 12, and 14 and Luna 16 sites.

^e Mare-type glass in soil 14259.

^f Mare-type glass in Apollo 15 soil.

Note: Preferred glass compositions similar to the local mare basalt occur in most soils.

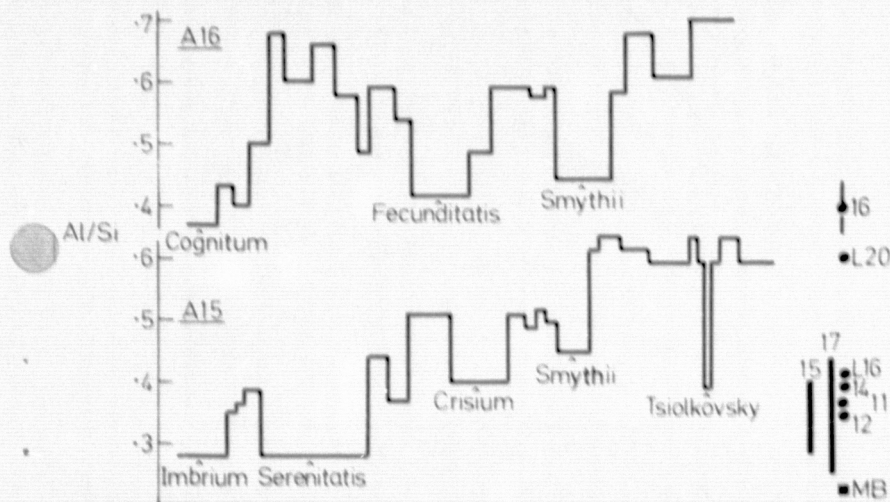


Figure 3 Al/Si atomic ratios for lunar regolith from orbital X-ray fluorescence data (Adler 1972a, b). Also shown are Al/Si ratios or ranges for samples of mare and terra soils. Note the low ratios for mare basalt (MB) and high ratios for mare geographically close to terra regions. This is almost certainly because of lateral mixing.

1970). The Al/Si ratios remain remarkably constant across the large mare basins, suggesting an efficient mixing of mare and terra materials, without significant compositional gradients towards the highlands. Because all the mare landing sites have been close to the highlands, it has not been possible to determine the extent of terra mixing with mare at sites distant from the highlands.

Trace Element Compositions

The large ion lithophile (LIL) trace elements generally show an affinity for the silicate melt phase during both melting and crystallization. Since crystal/melt distribution coefficients are reasonably well known for several of these trace elements in silicate phases [e.g. Rb, Sr, K, Ba, rare earth elements (REE)], their behavior during both melting and crystallization can be predicted with some confidence. Particular attention has been directed at the abundance patterns for mare basalts. The absolute abundances of LIL elements relative to chondritic abundances vary by an order of magnitude, the relative abundances less so (Figure 4). Some of the

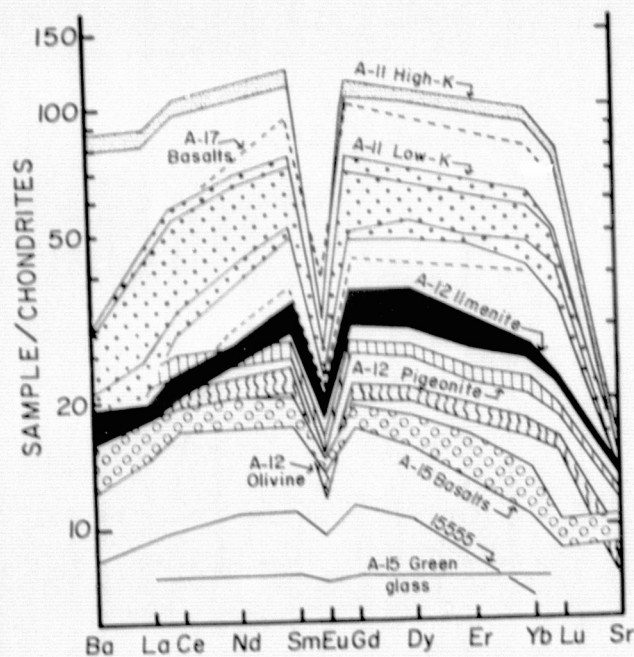


Figure 4 LIL trace element abundances for mare basalts and Apollo 15 green glass, normalized to chondritic abundances. Note the ubiquitous negative Eu anomaly and wide range in LIL elements. The Apollo 15 green glass has the least fractionated pattern but still maintains a small Eu anomaly. Note also the coherence of Eu and Sr and the cross-cutting relationship of some mare rare earth patterns. Data derived from Haskin et al (1970), Gast (1972), Rhodes & Hubbard (1973), Rhodes et al (1974).

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more important observations regarding the LIL element distributions are (a) the ubiquity of a negative Eu anomaly, (b) correlation of Sm/Eu ratio with absolute abundance of LIL elements, (c) chemical coherence between Eu and Sr, (d) weak fractionation of light relative to heavy rare earths and tendency for fractionation to increase with increasing atomic number and with absolute abundances, (e) lack of close coherence between K and less volatile LIL elements, and (f) fundamental differences in abundances of LIL elements and rare earth patterns between mare and terrestrial basalts.

Large Sm/Eu ratios indicate the important role played by plagioclase (a sink for Eu^{2+} but not for trivalent REE) at some stage in the generation of mare basalts, although other complex schemes not involving plagioclase have been evolved (Ringwood 1974). Model calculations (Haskin et al 1970) indicate that prohibitive amounts of plagioclase would have to separate from unfractionated mare magmas in order to produce the observed Sm/Eu ratios. Such a process would also be incompatible with the delayed crystallization of plagioclase in mare basalts (Ringwood & Essene 1970, Green et al 1971, Biggar et al 1971, Bence & Papike 1972).

Observation (Anders et al 1971) has led to the suggestion that the source for mare basalts would have $\text{Sm}/\text{Eu} \geq 1$ and that gradually decreasing degrees of partial melting give gradually increasing Sm/Eu ratios. In detail, however, there are many exceptions: the Luna 16 basalts have lower Sm/Eu ratios than might be predicted from the REE abundances, the Apollo 12 ilmenite basalts have REE patterns quite different from other mare basalts, and so on. This suggests multiple source regions for mare basalts.

Variations in Ce/Sm ratio indicate that clinopyroxene played a role in mare basalt genesis (Shih et al 1975), but Ce/Sm and Gd/Lu ratios show no well-defined relationship (the Gd/Lu ratios are strangely high in Apollo 15 basalts).

The coherence of Eu and Sr in mare basalts provides some clue to the crystallochemical behavior of Eu under lunar conditions. Such coherence could only be maintained if Eu were largely present as Eu^{2+} , in which case both Sr and Eu would display diadochy with Ca. It has generally been accepted that the low redox conditions under which lunar magmas evolve would result in $\text{Eu}^{2+}/\text{Eu}^{3+}$ ratios higher than observed in terrestrial basalts (Philpotts 1970, Drake et al 1974, Drake 1975). In this case, a large fraction of Eu as well as Sr would be locked in plagioclase, producing high Ce/Eu ratios in mare basalts equilibrated with plagioclase.

Fractionation of minerals at low pressure does account for some of the chemical variations in mare basalts (Table 3), but removal of reasonable amounts of olivine and chrome spinel cannot significantly perturb the relative LIL element distributions. Hence, it has generally been accepted that uniquely lunar patterns reflect processes operating within the lunar interior during the partial melting events giving rise to the mare basalts.

Important information has also been obtained from studies of siderophile and volatile elements in lunar rocks. Some of these elements, e.g. Ir, Re, Au, and Ni, are abundant and well characterized in meteorites, but are quite depleted in pristine

lunar rocks such as mare basalts; therefore they allow an estimate of the contribution of extralunar meteoritic material to the mare regolith (Figure 5). A striking characteristic of mare basalts is the depletion in volatile elements, relative to their terrestrial and meteoritic abundances (Figure 5). Since these volatiles may be siderophile, chalcophile, or lithophile in their chemical behavior, one crystal-liquid process within the Moon is unlikely to have initially produced such uniform depletions. This conclusion points towards a Moon that was born already depleted in volatile components, either as a result of accretion at too high temperatures to condense volatile elements, or a solar nebula that was itself depleted in these elements.

Some skepticism has prevailed, however: some people argue that volatile loss occurred during magma eruption into the lunar vacuum. This seems highly unlikely (Ganapathy et al 1970) because both Rb-Sr and U-Th-Pb systematics demonstrate loss of either Rb or Pb not at the time of basalt crystallization but rather at a time approaching that of the Moon's genesis. In addition, the low vapor pressures of these elements require extremely efficient exposure of all parts of the magma body to the lunar atmosphere (Gibson et al 1972), such as might occur during fire-fountaining. Because both quenched basalts and slowly cooled

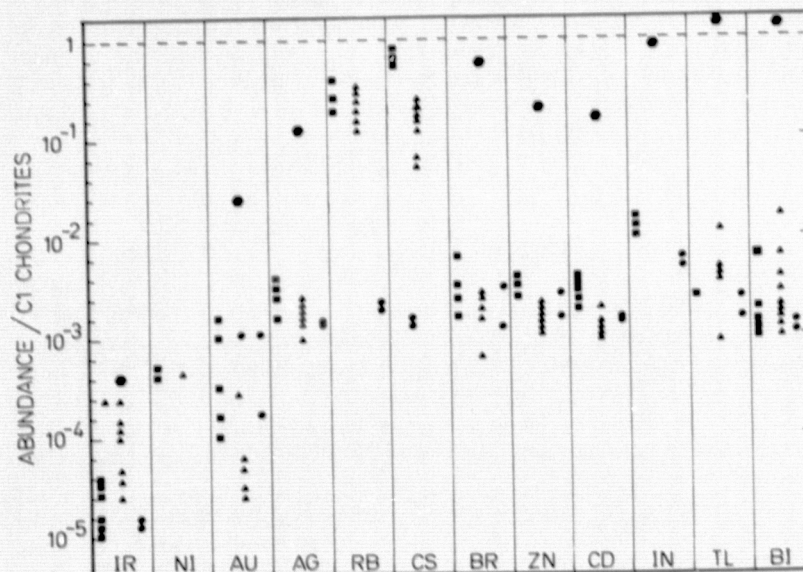


Figure 5 Abundance of siderophile elements (Ir, Ni, Ag, Au) and volatile elements in Apollo 11 (squares), Apollo 12 (triangles), and Apollo 15 (circles) mare basalts and terrestrial basalts (polygons), relative to CI chondrites. Br and Bi may also be siderophile, Zn and Cd chalcophile, and Rb, Cs lithophile. Note the dramatic depletions in all these elements relative to chondrites and terrestrial basalts. Data from Ganapathy et al (1970), Anders et al (1971), Morgan et al (1972).

gabbros are equally devolatilized, the conclusion that this characteristic was inherited from the lunar interior seems inescapable.

- The mare basalts are also drastically depleted in volatiles and siderophiles relative to terrestrial basalts; the latter are also much depleted relative to ordinary and hypersthene chondrites (Figures 5, 9). Some authors have used this difference to deduce that the Earth and the Moon are not genetically related (Singer & Bandermaun 1970), but such differences can also be explained if the Moon were produced as an Earth satellite (Ganapathy et al 1970). Removal of siderophile elements in a period of metal extraction may produce the observed differences, if the four to six orders of magnitude oxygen fugacity difference between the Earth and Moon are taken into account. Siderophile elements may have been much more strongly fractionated into the metal rather than the silicate phase within the Moon (Anders et al 1971).

Texture and Mineralogy

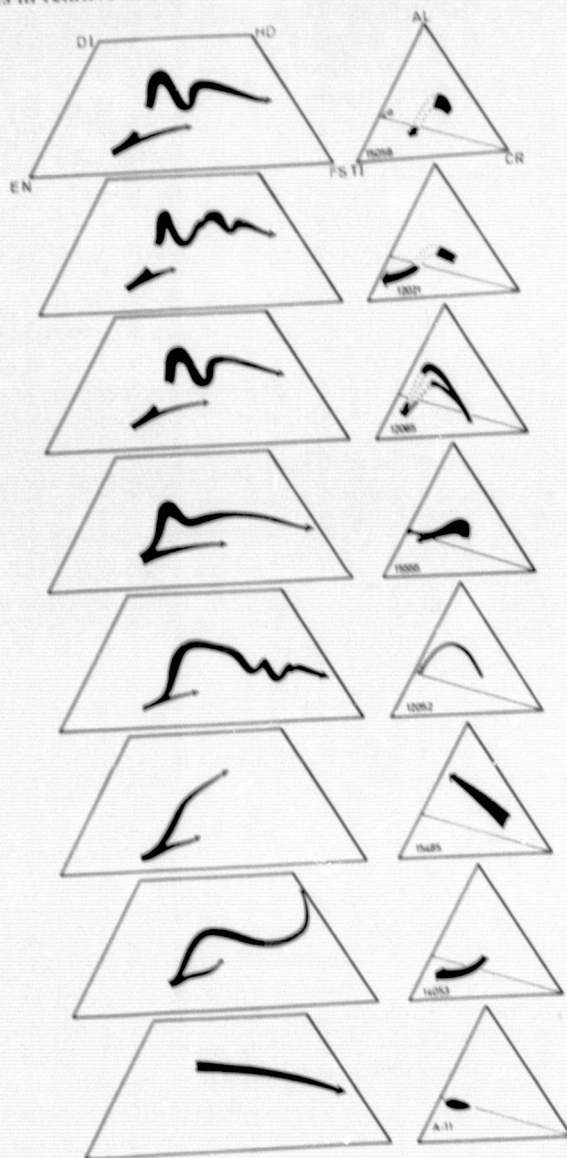
The two most important parameters affecting texture are viscosity and undercooling, the latter being necessary to promote any crystallization at all. Both parameters determine crystal growth and nucleation. The texture of mare basalts are the result of crystallization from silicate liquids derived from partial melting of the lunar mantle rather than as impact melts, a conclusion borne out by numerous trace element and isotopic studies (Papanastassiou et al 1970, Papanastassiou & Wasserburg 1970, 1972, Gast 1972). Green and orange glass collected during Apollo 15 and 17, respectively, may represent marelike magmas that underwent extreme undercooling. Aside from these, all mare magmas crystallized extensively, even where rapid cooling rates can be demonstrated. This is in marked contrast to terrestrial basalts, and reflects the lower viscosity and variable but higher degree of supercooling of mare magmas.

Both empirical and experimental observations (Dowty et al 1974a, Lofgren et al 1975) demonstrate that many mare basalts, including those with phenocrysts many times larger than ground-mass crystals, are the result of a one-stage, approximately linear cooling-rate superimposed upon varying degrees of undercooling. Based on crystallochemical grounds, it was previously argued that some mare basalts had undergone a two-stage cooling history (Boyd & Smith 1971, Bence et al 1971, Bence & Papike 1972).

A voluminous literature exists on the mineral chemistry of mare basalts, providing clues to cooling rate, crystallization history, elemental fractionation, oxygen fugacity and petrogenesis. Such studies provide an essential part of the classification of mare basalts. Most attention has been focused upon the pyroxenes and spinels, whose chemical variations are very large compared to the equivalent terrestrial mineral groups. In addition, mare basalts contain assemblages considered incompatible on the Earth (e.g. Mg-olivine and tridymite), assemblages unstable on Earth (e.g. Fe-Ni metal and troilite), and some uniquely lunar minerals (e.g. armalcolite and tranquillityite). Glossaries of lunar minerals may be found in Brown (1970), Levinson & Taylor (1971), Frondel (1972), and Taylor (1975).

Idealized elemental variations in mare pyroxenes are shown in Figure 6. Mare

pyroxenes characteristically cover much of the pyroxene quadrilateral, frequently plotting within the "forbidden zone" for terrestrial pyroxenes. Zoning is ubiquitous, complex, and extreme, involving large changes in Ca, Fe, Mg, Ti, Al, and Cr. Several authors have used zonal trends to separate different basalt classes, and in this respect, subtle changes in relative abundances of Al, Ti, and Cr may be successfully utilized.



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Generally, pyroxene chemistry is strongly determined by magma bulk chemistry, for example, the much larger absolute concentrations of Ti (and hence Al) in Apollo 11 and 17 pyroxenes. Al/Ti ratios are determined initially by bulk chemistry but later by the buffering effect of crystallization of other minerals, e.g. ilmenite and plagioclase. In some cases, the relative abundances of Al, Ti, Cr in late-stage, iron-rich pyroxenes can only be accounted for by assuming the presence of Ti^{3+} and/or Cr^{2+} .

In most mare basalts, with the exception of Apollo 11 and 17, the initial pyroxene to crystallize was Mg-pigeonite, or rarely hypersthene (Hollister et al 1971). The core low-Ca pyroxene may be sharply rimmed by, or gradationally pass into, a calcium-rich augite as a consequence of epitaxial growth. Further zoning involves progressive iron enrichment and possibly several excursions into the subcalcic, ferroaugite field. The ultimate crystallization is either Mg-free triclinic, pyroxenoid, pyroxferroite, or ferrohedenbergite. Complications arise if the pyroxene undergoes sector zoning (Ross et al 1970, Hollister et al 1971, Bence & Papike 1972, Dowty et al 1974a) in which [110] and [010] sectors of different composition grow. Note in Figure 6 the divergence of pyroxene trends in some cases is caused by sector zoning.

A number of circumstances may have given rise to the remarkable variations in pyroxene compositions (Brown et al 1970). These are (a) undercooling towards the cotectic in the subcalcic augite field (this does not explain the strong iron enrichment), (b) near-equilibrium crystallization of augite, largely in the absence of olivine, pigeonite or orthopyroxene, so that augite was no longer restricted to a solvus relationship, (c) availability of abundant Fe^{2+} in the melt relative to Mg, Ca allowing strong iron enrichment, (d) removal of Ca from the melt by crystallization of bytownite-anorthite (Bence & Papike 1972).

Plagioclase is more calcic than observed in terrestrial basalts, reflecting the

← Figure 6 (opposite) Idealized compositional trends in a variety of lunar pyroxenes. The pyroxene quadrilateral represents ideal end-members $CaMgSi_2O_6$ (DI = diopside), $CaFeSi_2O_6$ (HD = hedenbergite), $MgSiO_3$ (EN = enstatite), and $FeSiO_3$ (FS = ferrosilite). Two trends in some diagrams generally represent an 010 pigeonite trend and 110 augite trend in sector-zoned crystals. Note the tendency for late-stage pyroxenes to approach the magnesium-free join, resulting in the crystallization of the pyroxenoid, pyroxferroite. Triangles represent variations in minor elements Al, Ti, and Cr with crystallization. Note the Ti and Cr apices are at 50% Ti and 50% Cr, respectively. Detailed discussion to the use of this diagram may be found in Hollister et al (1971) and variations in Bence & Papike (1972). Line *a* represents an Al/Ti = 2/1. Note most pyroxenes approach or cross this line to Al/Ti < 2/1 at some stage in their cooling history. 12038 to 12052 approximately represents a sequence in which plagioclase appears progressively later in the crystallization sequence (Bence & Papike 1972); in 15485 plagioclase does not appear at all. Note the unique trend for 14053, which crystallized at lower P_{O_2} than most other mare basalts. Pyroxenes in Apollo 11 ilmenite basalts have Al/Ti ≥ 2 throughout their crystallization period. Note also that the position at which line *a* is intersected by the pyroxene trend is a rough guide to the beginning of plagioclase crystallization, except for 14053 and Apollo 11 pyroxenes.

very low alkali content of mare magmas. Zoning of more than 15 mol % anorthite is rare. Mare plagioclases also contain substantial ferrous iron and magnesian (Smith 1971), the Fe/Mg ratio increasing with fractionation (Crawford 1973). This relationship is potentially useful in distinguishing xenocrystic crystals and as a monitor of alkali loss during crystallization. Nonstoichiometry is frequently observed in mare plagioclases, which can only be partly explained by Fe^{2+} in tetrahedral sites. Rapid cooling may be an important factor (Weill et al 1970), but the observation that stoichiometric deviation correlates with bulk composition (Storey 1974), suggests that the structure of the mare melts may influence plagioclase stoichiometry.

Olivine crystallized in varying amounts in most mare basalts. In some Apollo 17 basalts, olivine seems to have had a reaction relationship with the melt, since rims of augite on olivine are frequently observed (Papike et al 1974). In Apollo 15 olivine basalts, much of the variation in bulk chemistry is due to variations in olivine content, probably as a result of low-pressure olivine settling. Zoning of olivine phenocrysts to about Fo_{40} has been observed, with a distinct compositional break to small amounts of pure fayalite in the mesostasis that suggests again a reaction relationship may hold. Unlike terrestrial basalts, forsterite and cristobalite crystallized simultaneously from mare basalts, although this may be a disequilibrium assemblage (Brown 1970).

The chemical variations and cationic substitutions in mare opaque phases is at least as complex as observed for mare pyroxenes, and much more variable than for opaques in terrestrial basalts. Probably the major nonterrestrial feature is the absence of magnetite or hematite solid solutions, which can be attributed to the lack of ferric iron. Instead, the major solid solutions involve complex substitutions of Fe-Mg, Al-Cr, Ti-Zr, so that ilmenite, members of the ulvospinel (Fe_2TiO_4)-picrochromite (MgCr_2O_4)-chromite (FeCr_2O_4)-hercynite (FeAl_2O_4), and members of the armalcolite series (MgTi_2O_5) have been described in mare basalts. Other opaque phases include Fe-Ni alloys and troilite, and several exotic Zr-rich minerals have also been identified.

Spinel compositional data in mare basalts have been summarized in the Luna 16 volume (Haggerty 1972b) and are shown in Figure 7. Chrome-rich spinels frequently crystallized first, followed by ulvospinel and finally ilmenite, representing different stable compositions as oxygen fugacity and temperature decreased. High temperature reduction of spinels has also been described (Haggerty 1972a), representing the antithesis of high temperature oxidation frequently observed in terrestrial igneous spinels (Watkins & Haggerty 1967).

Titania-rich basalts frequently contain armalcolite (an Mg-rich member of the pseudobrookite group), presumably in response to high Ti activity in the melt. Both observation and experiment support a limited stability range for armalcolite, which reacts with melt to produce ilmenite with decreasing temperature (Green et al 1975). Complex solid state reductions of armalcolite have also been reported (Haggerty 1973, Ridley & Brett 1973) involving the stabilization of ilmenite, ulvospinel, Al-spinel, and Fe metal.

A number of mesostasis minerals have been described from mare basalts, of which the most common is tranquillityite, a lunar mineral rich in zirconium. However,

this is just one of a complex solid solution series of minerals containing substantial Zr and rare earth elements that have no terrestrial counterparts.

Ages and Isotopic Compositions

Mare basalts have crystallization ages from 3.1 AE to 3.8 AE, as determined by Rb-Sr, U-Th-Pb and ^{39}Ar - ^{40}Ar methods. The titania-rich basalts from Tranquillity

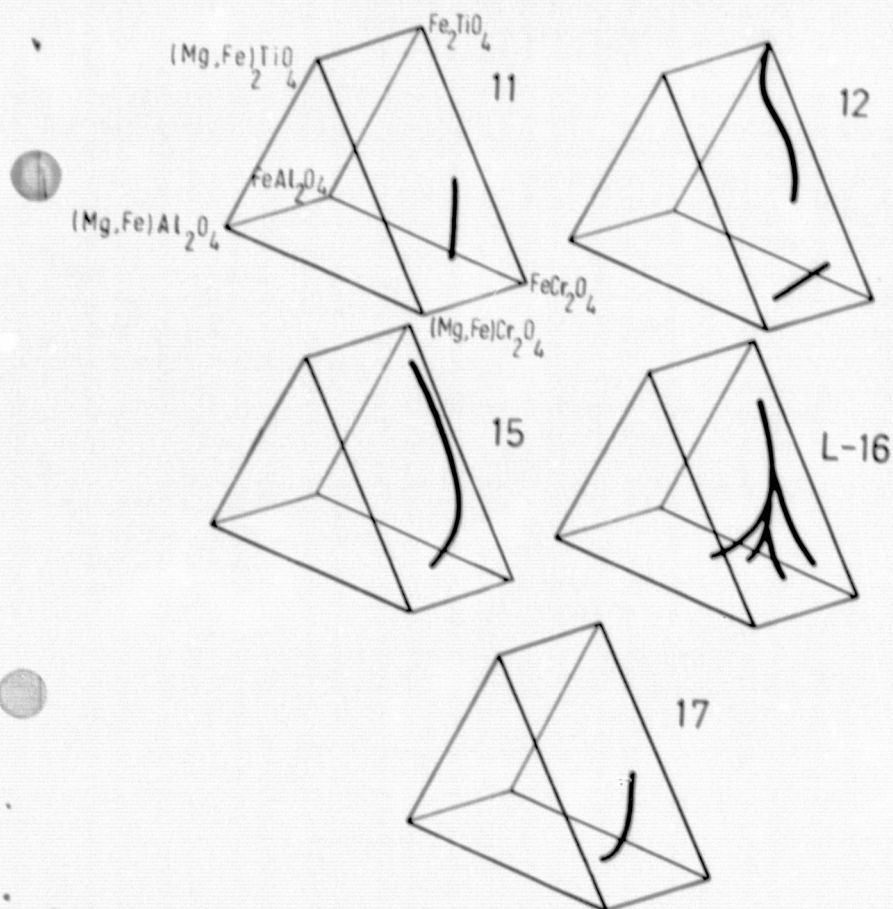


Figure 7 Idealized trends of spinel variation in mare basalts plotted in a modified Johnston prism (after Haggerty 1971). The end-members are described in the text. Note the similarity between Apollo 11 and 17 spinel trends, and Apollo 15 and 12 trends, except for a discontinuity in the latter and a greater variability in the chromite-picrochromite solid solution. Luna 16 spinels are similar but show greater hercynite-spinel solid solution and more variability in the ulvospinel-poor members. Data from Haggerty (1971, 1972b), El Goresy et al (1974).

and Serenitatis have consistently older ages (3.6–3.8 AE) than the low-titania basalts from Procellarum and Imbrium (3.2–3.4 AE). Basalt from Fecunditatis has been dated at 3.4–3.5 AE (Papanastassiou & Wasserburg 1972). Temporal changes in chemistry are indicated (Papike et al 1974), but the areal sampling is statistically poor and warrants cautious interpretation. Large scale volcanism must have ceased at about 3 AE, judging from crater densities on mare surface.

Rb-Sr systematics are rather straightforward, at least compared to terra samples, and suggest that the systems have remained undisturbed since the lavas cooled (Papanastassiou & Wasserburg 1972). The low Rb/Sr ratios, together with crystallization ages, indicate an origin of mare basalts by partial melting of a low Rb/Sr mantle (0.003–0.008) evolved essentially since 4.6 AE (Figure 8). This in turn indicates that low Rb/Sr ratios as a result of depletion in Rb were a characteristic of the Moon's mantle at approximately 4.6 AE.

Most mare basalts give discordant U-Pb ages (Tera & Wasserburg 1974); Concordant basalts (Nunes et al 1974, Tera & Wasserburg 1974) with intersections at ~4.4 AE, are rarely observed, which implies no fractionation of Pb and U in these basalts relative to their source. Tera & Wasserburg (1974) discuss several ways such an unlikely situation might arise. The evolutionary history of the discordant mare basalts must be complex and highly dependent on the multistage model chosen. Preliminary U-Pb internal isochron determinations (Tera & Wasserburg 1974), which are model determined, again indicate an important event at ~4.4 AE in the evolution of the lunar mantle.

Experimental Petrology

Much of the rhetoric and argument on mare basalts has centered upon the interpretation of high-pressure and temperature-melting experiments. Such heated debate reflects the inherent importance of this discipline in determining the origin of mare basalts and the mineralogy of the lunar mantle. Reduced to its simplest

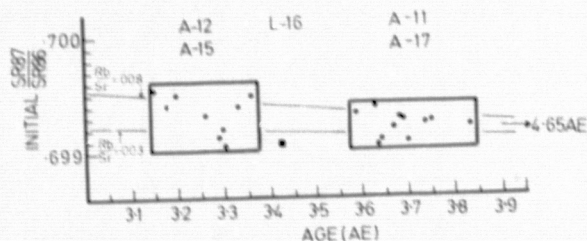


Figure 8. Rb-Sr systematics for mare basalts. Note the two groups corresponding to overall similarities in bulk chemistry. Two lines of Rb/Sr = 0.003 and Rb/Sr = 0.008 roughly bracket the Rb/Sr ratio of the mare source regions that could have evolved from $^{87}\text{Sr}/^{86}\text{Sr} = 0.69898$ (initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of basaltic achondrite meteorites since 4.65 AE and produced mare basalts at the intervals shown without previous fractionation of the Rb/Sr ratio. Data are from Compston et al (1970, 1971), Papanastassiou et al (1970), Papanastassiou & Wasserburg (1970, 1972), Nyquist et al (1972), Evensen et al (1973).

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terms, and ignoring the esoteric complexities of "run conditions," the arguments revolve around the degree to which mare basalt chemistry has been perturbed by low pressure fractional crystallization. If this process has operated in a major way, then experiments that simulate mantle pressures cannot be used to evaluate phase relations in the Moon's mantle; conversely, if the basalts are pristine and largely unfractionated melts, such experiments provide valuable information.

Much of the information previously discussed indicates that some low pressure fractional crystallization should occur in lavas of such low viscosity. This process is likely to have operated most effectively in the high-titanium basalts that crystallized abundant, dense iron-titanium oxide. However, both textural evidence and low pressure cooling experiments clearly demonstrate that the presence of abundant phenocrysts cannot be an unequivocal test for a high degree of crystal settling. At least some of the mare basalts arrived at the lunar surface as liquids and justifiably can be used for high pressure experiments (Grove et al 1973, Longhi et al 1974).

High-titanium basalts are multiply saturated, or nearly so, with olivine + clinopyroxene + ilmenite + spinel at pressures corresponding to 100-150 km (Ringwood & Essene 1970, Longhi et al 1974). Some experimentalists (Longhi et al 1974) accept this as the depth range in which mare basalts are produced. Others (Ringwood & Essene 1970) argue that heat flow considerations require the zone of partial melting to be deeper (200-400 km), which according to experimental data would indicate a mantle dominated by low-calcium pyroxene (pyroxenite).

In contrast, experimental data for low-titanium, picritic basalt, carefully selected for its primitive nature (Grove et al 1973), indicate a source mineralogically unlike the source of high-titanium basalts. Extended liquidus crystallization of olivine at low pressure and low-calcium pyroxene at higher pressure is unlike the multiply saturated liquid noted above.

The Sources of Mare Basalts

Assuming that some mare basalts are primitive enough to render high pressure experiments relevant, there are two model-dependent sources for mare basalts. According to the first model, mare basalts were produced by partial melting of a pyroxenitic mantle at depths between 200-400 km, determined by the fluctuating position of the melting zone with time (Wood 1972, Toksoz 1974). In this model (Ringwood & Essene 1970, Green et al 1971) the sources of the high-titanium and low-titanium basalts are very similar and do not require the presence of substantial ilmenite. Production of the LIL element abundances and the ubiquitous europium anomaly require disequilibrium melting but do not require the presence of plagioclase. In the second model, mare basalts were produced at less than 150 km depth by partial melting of cumulates containing substantial pyroxene, ilmenite, and olivine. Heat sources to remelt such a refractory assemblage have not been satisfactorily located. The cumulates are the product of an early lunar differentiation and have a negative Eu anomaly, which is then inherited by the mare melts. By this scheme the low-titanium and high-titanium basalts cannot have the same source. Ilmenite plays an essential part in generating high-titanium melts.

Other conclusions that are not model-determined can be drawn. The mare source

was depleted in volatile trace elements by two orders of magnitude over chondritic abundances (Figure 9). Radiometric considerations indicate this was a primitive feature developed at ~ 4.6 AE, which corresponds to the Moon's inception as a planet. The mare sources are also depleted in siderophile and chalcophile elements, some of which are also volatile, suggesting early removal in metal and sulphide phases. For reasonable degrees of partial melting (1–10%) the source would be enriched 5–10 times over chondritic abundances in refractory LIL elements, perhaps reflecting an earlier period of enrichment during mantle formation. For a cumulate source, the LIL elements may have resided in intercumulus material.

TERRA ASSEMBLAGES

With few exceptions, samples collected from the lunar terra have clastic and/or metamorphic textures. These textures are believed to be a consequence of intense meteorite bombardment, which fragmented, shocked, annealed, partially melted and recrystallized the terra rocks. During this process, pristine, igneous textures were modified extensively, sometimes up to the point of obliteration. In this sense, the terra rocks contrast vividly with the mare basalts, which still retain pristine igneous textures and mineral assemblages. Our limited knowledge of physical and chemical changes attendant upon meteorite impact has led to a renewed interest in terrestrial

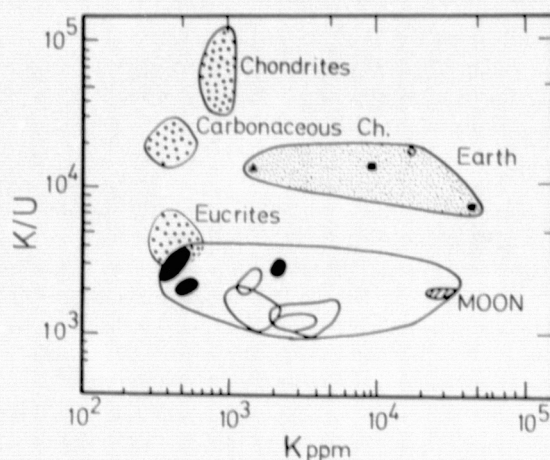


Figure 9 K concentrations normalized to a constant Si concentration of 18.5, and K/U ratios for lunar, meteoritic, and terrestrial samples. Range of values for mare basalts shown as solid areas; other areas are mare soils and breccias, except for the shaded area (12013). Specific rock types identified amongst terrestrial rocks are oceanic tholeiite (triangle), continental tholeiites (square), andesite (open circle), and granite (filled circle). Modified after Gast (1972).

Note that the low K/U of the Moon is not characteristic of all meteorites; ordinary and enstatite chondrites have significantly higher ratios.

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impact craters (Chao 1974, Grieve et al 1974) in the hope that such studies may have application to terra breccias.

Rare, but nonetheless important, coarse-grained rocks occur in terra assemblages. These show no evidence for extensive meteoritic reworking and are thought to represent deeper parts of the lunar crust that were occasionally excavated during particularly intense bombardment. In the next section these rocks are discussed separately from the petrochemistry of terra breccias. Space considerations require us to deal cursorily with the terra soils that form a thick veneer over the terra bedrock. Figure 10 indicates the physiochemical processes operating to produce and modify lunar soils.

Breccias and Soils

Petrographic and chemical data indicate that impact may crush, shock, partly or wholly remelt, partly volatilize, and metamorphose bedrock. A minimal effect would be mild thermal induration of disaggregated material, e.g. regolith to produce a rather friable "rock," commonly called a regolith or soil breccia. At the other extreme, total melting may have occurred so that the rock acquired a completely new texture.

Two research fields have developed in breccia studies. Firstly, there are studies toward understanding the process of brecciation and how breccias evolve at or near the lunar surface. In these cases particular emphasis is placed upon matrix textures. Secondly, there are studies using breccias as carriers of previous lithologies; particular emphasis is placed upon vitric, crystalline, and lithic clasts within the breccias.

Breccias are commonly the product of many impact events and are polymict

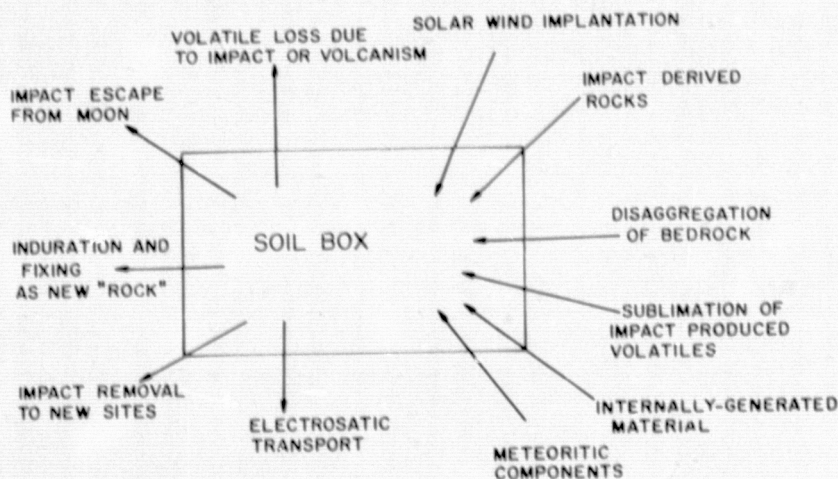


Figure 10 Idealized diagram illustrating various chemical and physical inputs to and outputs from the lunar "soil box."

rocks with several generations of brecciated clasts, best exemplified at the Fra Mauro site. Monomict breccias, representing one or a few minor impacts into a homogeneous target are rather rare. Useful criteria for recognizing mature breccias are high siderophile element content as a result of admixture of meteorite components; high metallic iron content as a result of long exposure to the reducing solar wind, high solar wind components; and high fission track density. Clastic matrix and overall inequigranular texture also help to separate breccias from primary igneous rocks. All of the criteria are most easily applied to low-grade breccias that have not been subjected to temperatures above about 700°C over long periods of time. Outgassing of breccias, annealing of fission tracks, volatile loss, and resorption of clasts into matrix take place at more elevated temperatures, obscuring the prehistory of the breccia (Tera et al 1970). If carried to extremes, breccia textures approach those of pristine igneous rocks, ultimately leading to debate as to the origin of high-grade metamorphic rocks (somewhat reminiscent of the granite controversy).

Regolith-or-soil-breccias have heterogeneous matrices, shock-produced matrix glass, and a notable porosity (Christie et al 1973). Increased shock may lead to plastic deformation, heating, loss of porosity and formation of a recrystallized, cryptocrystalline, isotropic matrix. These lithification processes probably occur in situ, involving propagation of a shock wave through loose soil, and do not develop in thick impact ejecta blankets.

The most successful and widely applicable breccia classifications are based upon matrix textures (Warner 1971, 1972, Warner et al 1973, Wilshire et al 1973, James 1974, Simonds et al 1974), because increasing breccia grade involves a continuous variation in matrix texture and mineralogy.

Much controversy has centered on the origin of high-grade breccias with granulitic, poikilitic, subophitic, and ophitic textures. Such breccias are abundant at the Cayley-Descartes Mountains and Taurus-Littrow Valley and to a lesser extent at all other terra sites. Arguments center upon the presence and amount of a melt phase and environment of formation. In the poikilitic textures are largely the result of solid state metamorphic recrystallization, then this might occur in a thermally insulated, thick ejecta blanket. Conversely, the presence of a substantial melt phase ($> 10\%$) would indicate origin as an impact melt. Evidence from terrestrial craters suggests that these textures are associated with 20-60 km diameter craters (Grieve et al 1974) and are a function of stratigraphic position within the impact melt.

Cataclastic textures are typically developed in bedrock lining impact craters. Cataclastic anorthosites, anorthositic gabbros, norites, and dunites—displaying varying degrees of recrystallization, brecciation and deformation—have all been found at terra sites. More complex breccias indicating injection of fragment-laden impact melt may represent fallout or fallback breccias associated with major impacts.

Chemically, terra breccias are very variable, as shown in Figure 11. The Fra Mauro breccias display the least variability, being dominated by an aluminous basaltic component rich in LIL trace elements and designated KREEP basalt. Exceptions are the white breccias excavated from Cone Crater, which are more aluminous and contain no significant KREEP component. Brown-glass matrix

breccias dominate the stratigraphy of the Apennine Front (Phinney et al 1972) and also have a basaltic composition, but only have about one third of the LIL elements of KREEP basalt.

The most feldspathic terra breccias occur in the Cayley-Descartes highlands, including cataclastic anorthosites and light-matrix breccias, chemically equivalent

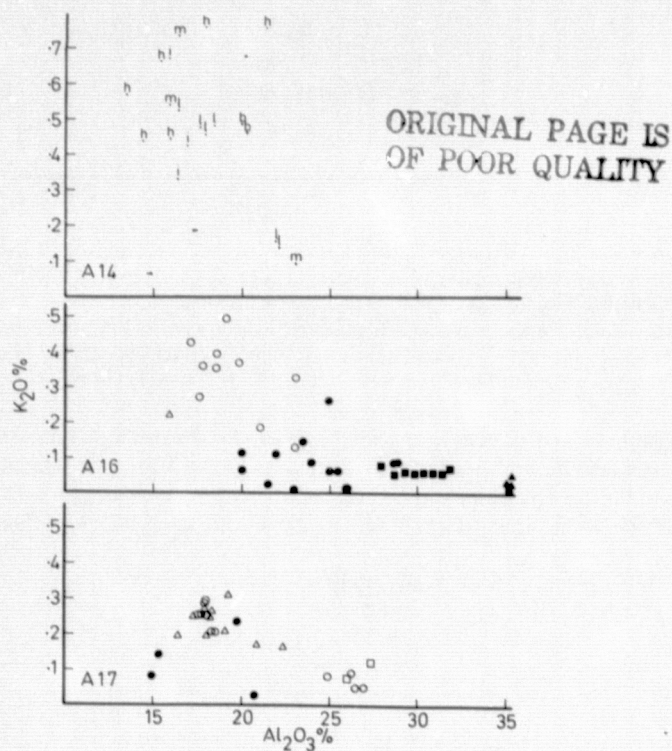


Figure 11 $K_2O-Al_2O_3$ plot for terra breccias from Apollo 14, 16, and 17. Al_2O_3 is a reflection of the feldspathic component and K_2O of the KREEP component (Simonds et al 1974). Apollo 14: high (*h*), medium (*m*), and low (*l*) grade breccias and basalts (*b*); data from Hubbard et al (1972), Laul et al (1972), Rose et al (1972), Taylor et al (1972), Willis et al (1972). Apollo 16: mesostasis-rich breccias and basalts (open circles), poikilitic breccias (filled circles), light-matrix breccias (filled squares), cataclastic anorthosite (filled triangles); data from Duncan et al (1973), Hubbard et al (1973), Laul & Schmitt (1973), Rose et al (1973). Apollo 17: subophitic breccias (open triangles), others as above; data from Simonds et al (1974). Breccia descriptions usually refer to matrix texture.

Note: (a) the overwhelming frequency of KREEP breccias at the Apollo 14 site, (b) a distinct division between poikilitic and mesostasis-rich breccias at the Apollo 16 site and abundant, highly aluminous ($>30\%$ Al_2O_3) breccias, and (c) general lack of KREEP-like breccias at the Apollo 17 site and different compositions for poikilitic rocks compared to the Apollo 16 rocks.

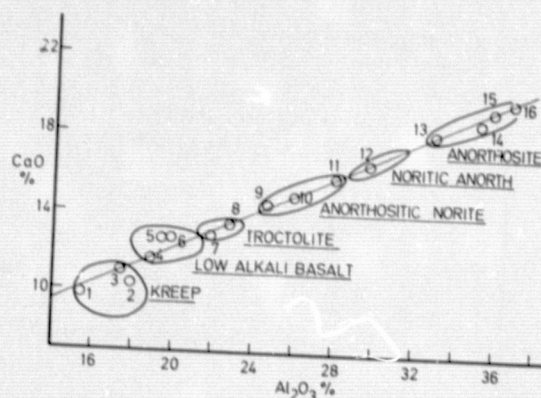


Figure 12 Major terra rock types plotted in terms of CaO and Al_2O_3 . Individual rock type averages (open circles) are as follows: (1) Apollo 15 high-K KREEP glass, (2) Luna 20 KREEP lithics, (3) Apollo 15 medium-K KREEP glass, (4) Apollo 15 glass, (5, 6, 7) lithics, glass, and rocks in Luna 20, (8) Luna 20 lithics (9, 10) lithics and glass in Luna 20, (11) Apollo 16 glass, (12) Luna 20 glass, (13) Luna 20 lithics, (14) Apollo 14 glass, (15) rock 15415, (16) anorthite. Data from Reid et al (1972, 1973b, c), Prinz et al (1973c).

to gabbroic anorthosite. In general, however, there seems little relationship between matrix texture and chemistry if Apollo 16 and 17 breccias are compared. The variations in chemistry can be accounted for by physical mixing of a few major rock types, including KREEP basalt, anorthosite, troctolite, and dunite.

Table 5 Suggested fundamental terra rock types

	a	b	c	d	e	f	g
SiO_2	48.01	45.84	44.57	43.98	44.29	43.06	39.93
TiO_2	2.02	0.78	0.37	0.33	0.05	0.17	0.03
Al_2O_3	17.12	21.16	25.84	29.75	34.60	23.66	1.53
Cr_2O_3	—	0.17	—	0.05	0.08	0.30	—
FeO	10.56	8.34	5.22	3.70	0.77	4.48	11.34
MgO	8.72	10.41	7.38	4.97	0.85	14.50	43.61
MnO	—	0.12	—	0.05	0.01	0.09	0.13
CaO	10.77	12.77	14.84	16.81	18.89	12.95	1.14
Na_2O	0.71	0.39	0.41	0.33	0.50	0.32	—
K_2O	0.60	0.11	0.09	0.05	0.02	0.05	—

^a KREEP basalt, Fra Mauro basalt. Large rocks, lithic fragments, glasses.

^b Low-alkali, high-alumina basalt; low-K Fra Mauro basalt. Occur in glass populations and lithic fragments.

^c Anorthositic norite, anorthositic gabbro, highland basalt, feldspathic basalt, ANT norite. Occur as large rocks, lithic fragments and glasses.

^d Gabbroic anorthosite, noritic anorthosite. Large rocks, lithic fragments, glasses.

^e Anorthosite. Large rocks, lithic fragments, glasses.

^f Troctolite. Lithic fragments.

^g Dunite. Lithic fragments.

Fundamental Terra Rock Types

In evaluating fundamental terra rock types, emphasis has been placed upon rare terra clasts with pristine igneous textures, and the recurrence of rocks with similar chemistry at several highland sites (Figure 12). Consistently similar rock types emerge from analyses of large rocks, lithic fragments, and impact glasses, as shown in Table 5 and Figure 13. Only some of these can be shown to have unequivocal igneous textures.

Terra rock types can be divided into those with fundamentally basaltic chemistry, i.e. KREEP basalt and low-alkali, high-alumina basalt, which are considered to have originated as melts, and those with compositions that deviate considerably from any reasonable liquid line of descent. These latter rocks are considered to be cumulates from basaltic magmas and include troctolites, spinel troctolites, norites, noritic anorthosites, anorthosites, and dunites.

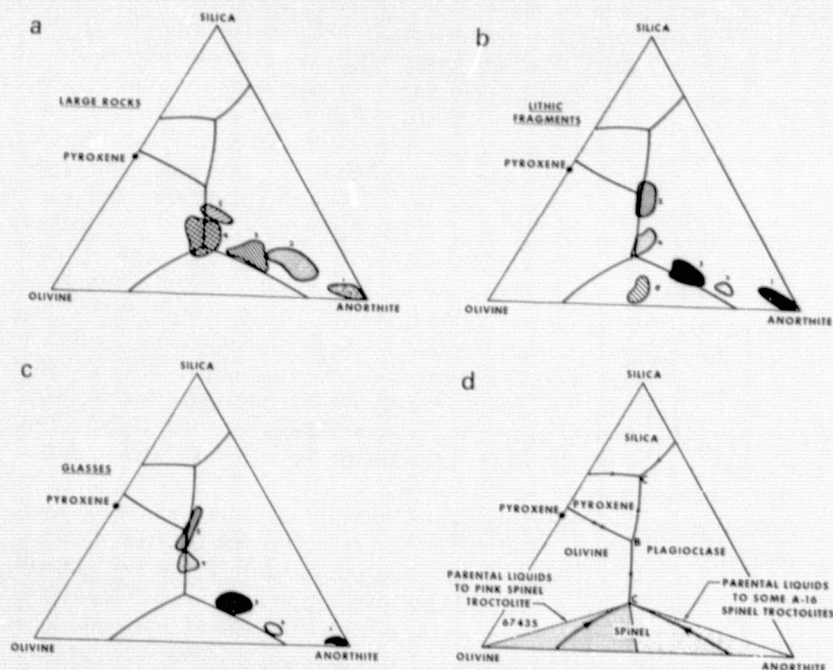


Figure 13 Bulk compositions of major terra rock types recalculated into normative olivine, anorthite, and quartz, and plotted in the pseudoternary system olivine-anorthite-silica. Phase boundaries are after Walker et al (1972). Individual fields are (1) anorthosite, (2) noritic anorthosite, (3) anorthositic norite, (4) low-alkali, high-alumina basalt, (5) KREEP, (6) (spinel) troctolite. Average compositions from large rocks (a), lithic fragments (b), and glasses (c). In (d), shaded areas represent possible parental liquids to some A-16 troctolites, assuming they are cumulates and based upon the cumulus and intercumulus phases. Note most troctolites could be derived, according to this diagram, from liquids lying close to peritectic point C.

KREEP Basalt with well-developed igneous texture has been sampled at the Apollo 14, 15, and 16 sites. However, the high siderophile and chalcophile element contents of some Apollo 14 KREEP indicates it was locally formed by impact melting [Morgan et al (1972), but see Crawford & Hollister (1974) for an opposing view]. Most KREEP basalt clasts have very low contents of meteoritic elements and are undoubtedly endogeneous to the Moon. As the acronym implies, this basalt type is rich in potassium, rare earth elements, and phosphorus. It is generally very enriched in LIL trace elements, including Th and U and presents a unique signature to the orbital gamma-ray data (Metzger et al 1973, Metzger et al 1974), indicating KREEP has a distinct provinciality to the Imbrium-Procellarum region. This is consistent with the dominance of KREEP basalt at the Fra Mauro site compared to at all other highland regions. Impact processes have tended to distribute KREEP in small amounts throughout the terra regions. KREEP basalt can be distinguished from mare basalts by high LIL element abundances, distinctive rare earth pattern (Figure 14), and high-alumina and low-titania content. KREEP basalts crystallize calcic plagioclase (An 94-58) as liquidus phase, followed by magnesian orthopyroxene containing about 3% Al_2O_3 . Orthopyroxenes are zoned continuously to pigeonite and ferropigeonite with only rare metastable pyroxene compositions (cf mare pyroxenes). In some slowly cooled KREEP gabbros, microscopic exsolution of augite and ferroaugite from pigeonite may be observed (Figure 13). Spinel is much less abundant than in mare basalts, and they include ilmenite and ulvospinel-rich phases (Haggerty 1972b) that occasionally have undergone subsolidus reduction to ilmenite and metallic iron.

Low-alkali, high-alumina basalt has been recognized as lithic fragments and preferred glass compositions, particularly in the Apollonius region (Prinz et al 1973c, Reid et al 1973c), but also at the Apollo 15 and 16 sites. Even in lithic fragments, the textures are commonly high-grade metamorphic textures, and it cannot easily be demonstrated that these rocks were initially magmas. At the Apollo 15 site some low-alkali basalts are polymict breccias (Phinney et al 1972). This basaltic composition is essentially similar to KREEP but with higher TiO_2 , Mg/Fe ratio, about one third of the LIL element concentrations, and a similar REE pattern (Figure 14).

Anorthosites were first recognized as lithic fragments in Mare Tranquillitatis soil (Wood 1972) and surmised at that time to be derived from the terra regions. They have been recognized dominantly as lithic fragments in soils (Taylor 1972, Dowty et al 1974b)—rarely as large samples (James 1972)—and form a small population in impact glasses (Reid et al 1972). Many anorthosites are believed to be genetically related to terra norites and troctolites and form part of the "ANT" suite of terra assemblages. Calcic plagioclase forms 85-95% of the rock and has a very restricted composition (An 98-94). Ferromagnesian minerals include olivine (Fo 90-55) and calcium-rich and calcium-poor pyroxene (Taylor 1972, Dowty et al 1974b, Drake et al 1974). Textures are either cataclastic or granoblastic, and the origin of these rocks as essentially monomineralic cumulates is based upon their extreme chemistry and the abnormally high temperatures required to generate them as liquids. Anorthosites have distinctive trace element abundances, being low in siderophile and chalcophile elements, but some are unusually enriched in volatile elements such as lead

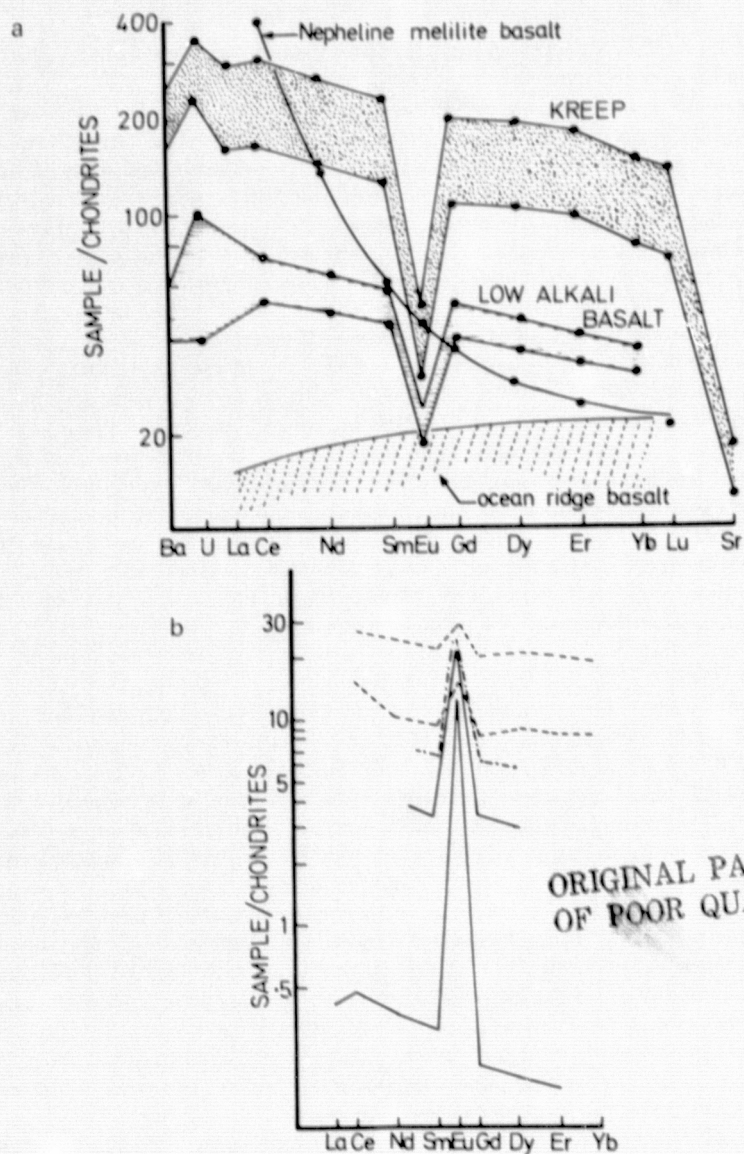


Figure 14 Lithophile trace element abundances in (a) terra basaltic rocks and (b) terra cumulate rocks. Abundances are normalized to chondritic abundances. In (a), patterns for terrestrial nepheline-melilite basalt and ocean ridge basalt are shown for comparison. In (b) are shown range for anorthosites (continuous lines), norite (broken lines), and the lower limit for troctolites (dash-dot line). Other troctolites have large negative Eu anomalies and up to 100 times the chondritic abundances of rare earths. Data from Hubbard et al (1972, 1973), Drake et al (1974).

and thallium. They also contain low LIL element concentrations except for enrichment in Eu giving a characteristic rare earth pattern (Figure 14).

Troctolites and spinel troctolites occur as lithic fragments in soils at most terra sites and as larger samples at the Apollo 16 and 17 sites. They are principally composed of olivine with plagioclase, spinel, minor pyroxene, and metallic iron (Prinz et al 1973b, Gooley et al 1974). Those with olivine and pink spinel have intercumulus plagioclase and have well-defined cumulate textures (Prinz et al 1973b). On the basis of mineralogy and texture, some troctolites are considered to be parts of deep crustal cumulates (Gooley et al 1974), although this remains contentious (Albee et al 1975). The LIL trace element composition of this group is not well defined, being largely controlled by the volume of intercumulus mesostasis present (Drake et al 1974). Where the groundmass is negligible, the rocks have low absolute LIL abundances and positive Eu anomalies (Figure 14), but with increasing mesostasis the absolute abundances increase and negative Eu anomalies appear.

Norites have been observed as lithic fragments and preferred groups in terra impact glasses, but rarely as large rocks. Metamorphic textures predominate. These rocks are principally composed of calcic plagioclase and orthopyroxene with minor clinopyroxene and olivine. With increasing plagioclase content they grade into anorthositic norites and noritic anorthosites. Although large rocks with these latter compositions have been found at the Apollo 15, 16, and 17 sites, their textures have been extremely perturbed by impact processes.

Petrogenesis of Terra Rocks

Numerous schemes have been evolved to account for the mineralogy and chemistry of terra samples within a framework of lunar crust and mantle evolution (Wood et al 1970, Smith et al 1970, Taylor & Jakes 1974, Taylor & Bence 1975). Although these models have become more sophisticated as more data has accumulated, the basic mechanism for crust-mantle evolution remains the operation of extremely efficient crystal fractionation within a moon-wide silicate melt. This was first proposed following the Apollo 11 mission (Smith et al 1970).

In a gross sense the formation of the lunar crust and mantle as complementary cumulates is suggested by (a) the inferred negative Eu anomaly for the lunar upper mantle (Nava & Philpotts 1973) and positive Eu anomaly for the terra crust (Taylor et al 1973); (b) the high Fe/Mg ratio of the mare basalts (derived from the upper mantle) compared to the low Fe/Mg ratio of terra rocks; (c) the high density of upper mantle minerals (olivine, orthopyroxene, clinopyroxene, ilmenite) compared to plagioclase that dominates the crust; and (d) the terra rocks and mare basalts that lie on opposite sides of the meteoritic Ca/Al line.

In detail, however, it is evident that the terra rocks, particularly the cumulate rocks, represent several stages in the evolution of the crust. Those with magnesian ferromagnesian minerals may be related to early crustal formation when plagioclase was separating with ferromagnesian minerals having a high Mg/Fe ratio. The implication here would be that the initial ferromagnesian minerals that largely sank should have produced an upper mantle whose deep regions had a high Mg/Fe ratio. However the extreme range observed in Fe/Mg ratios of olivines and pyroxenes

in terra cumulates strongly suggests some cumulates developed from highly fractionated silicate melts. Separation of early magnesian olivine and orthopyroxene from the primitive melted outer shell would result in residual melts with increasing Fe/Mg ratio (Taylor & Jakes 1974) but would also correspond to a drastic decrease in the amount of plagioclase precipitating and accumulating. It seems most unlikely that the more iron-rich cumulate members of the anorthosite-norite-troctolite suite could form by this process.

Once the crust had developed, the meteorite flux would still be very substantial, producing very extensive areas in which crustal remelting occurred. Some of the presently observed crustal cumulates may have developed in these "secondary" magma systems, basically unrelated to the development of the protocrust. Such magmas, if in equilibrium with plagioclase would have large negative Eu anomalies (Haskin et al 1970) and may account for the presence of terra rocks with large Eu depletions relative to trivalent REE. It is also clear that the source of KREEP magmas need not contain substantial plagioclase ($< 10\%$) (Weill et al 1974) and may represent partial melting of olivine and orthopyroxene cumulates, with minor plagioclase near the base of the lunar crust.

EPILOGUE

Lunar petrology is a very large and complex subject, involving many interrelated disciplines. We have probably accumulated more petrologic information on lunar rocks than any one type of terrestrial rock, and certainly more disciplines have been brought to bear on lunar rocks. One might surmise that similar broad-based approaches to terrestrial petrologic problems might lead to the surprising conclusion that terrestrial igneous and metamorphic rocks are much more complex than we presently consider them to be. In the lunar case, the broad brush scenario of lunar evolution has been constructed. The added problem of dealing with meteorite bombardment and the huge physicochemical perturbations this causes to rocks has insured that no physicochemical evolutionary scheme, satisfying in detail, has yet been put together. It remains a challenging intellectual exercise.

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Literature Cited

- Adler, I., Trombka, J., Gerard, J., Lowman, P., Schmadebeck, R., Blodgett, H., Eller, E., Yin, L., Lamothe, R., Osswald, R., Gorenstein, P., Bjorkholm, P., Gursky, H., Harris, B., Golub, L., Harnden, F. R. 1972a. Apollo 16 X-ray fluorescence experiment. *Apollo 16 Prelim. Sci. Rep. NASA SP-315*, Sect. 19, pp. 1-14.
- Adler, I., Trombka, J., Gerard, J., Lowman, P., Schmadebeck, R., Blodgett, H., Eller, E., Yin, L., Lamothe, R., Gorenstein, P., Bjorkholm, P. 1972b. Apollo 15 geo-

- chemical X-ray fluorescence experiment: preliminary report. *Science* 175:436-40
- Albee, A. L., Dymek, R. F., DePaolo, D. J. 1975. Spinel symplectites: High-pressure solid-state reaction or late-stage magmatic crystallization. *Lunar Science VI*, 1-3. Houston: Lunar Sci. Inst.
- Anders, E., Ganapathy, R., Keays, R. R., Laul, J. C., Morgan, J. W. 1971. Volatile and siderophile elements in lunar rocks: Comparison with terrestrial and meteoritic basalts. *Proc. Lunar Sci. Conf.*, 2nd 2: 1021-36. Cambridge: M.I.T. Press
- Bence, A. E., Papike, J. J., Lindsley, D. H. 1971. Crystallization histories of clinopyroxenes in two porphyritic rocks from Oceanus Procellarum. *Proc. Lunar Sci. Conf.*, 2nd 1: 559-74. Cambridge: M.I.T. Press
- Bence, A. E., Papike, J. J. 1972. Pyroxenes as recorders of lunar basalt petrogenesis: Chemical trends due to crystal-liquid interaction. *Proc. Lunar Sci. Conf.*, 3rd. *Geochim. Cosmochim. Acta* 1: Suppl. 3, pp. 431-69
- Biggar, G. M., O'Hara, M. J., Peckett, A., Humphries, D. J. 1971. Lunar lavas and the achondrites: Petrogenesis of proto-hypersthene basalts in the maria lava lakes. *Proc. Lunar Sci. Conf.*, 2nd. *Geochim. Cosmochim. Acta* 1: Suppl. 2, pp. 617-43
- Boyd, F. R., Smith, D. 1971. Compositional zoning in pyroxenes from lunar rock 12021, Oceanus Procellarum. *J. Petrol.* 12: 439-64
- Brown, G. M. 1970. Petrology, mineralogy and genesis of lunar crystalline igneous rocks. *J. Geophys. Res.* 75: 6480-96
- Brown, G. M., Emeleus, C. H., Holland, J. G., Phillips, R. 1970. Mineralogical, chemical, and petrological features of Apollo 11 rocks and their relationship to igneous processes. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 1: Suppl. 1, pp. 195-219
- Brown, G. M., Emeleus, C. H., Holland, J. G., Peckett, A., Phillips, R. 1971. Pierite basalts, ferrobasalts, feldspathic norites, and rhyolites in a strongly fractionated lunar crust. *Proc. Lunar Sci. Conf.*, 2nd 1: 583-600. Cambridge: M.I.T. Press
- Brown, G. M., Emeleus, C. H., Holland, J. G., Peckett, A., Phillips, R. 1972. Petrology, mineralogy, and classification of Apollo 15 mare basalts. *The Apollo 15 Lunar Samples*, 40-44. Houston: Lunar Sci. Inst.
- Brown, G. M., Peckett, A., Emeleus, C. H., Phillips, R. 1974. Mineral-chemical properties of Apollo 17 mare basalts and terra fragments. *Lunar Science V*, 89-91. Houston: Lunar Sci. Inst.
- Bryan, W. B., Adams, M. L. 1973. Some volcanic and structural features of Mare Serenitatis. In *Apollo 17 Prelim. Sci. Rep.*, NASA SP-330, Sect. 29, pp. 26-28
- Cadenhead, D. A. 1973. Lunar volcanic glasses and cinder formation. *EOS. Trans. Am. Geophys. Union* 54: 582
- Chao, E. C. T. 1974. Impact cratering models and their application to lunar studies—a geologists view. *Proc. Lunar Sci. Conf.*, 5th. *Geochim. Cosmochim. Acta* 1: Suppl. 5, pp. 35-52
- Christie, J. M., Griggs, D. T., Heuer, A. H., Nord, G. L., Radcliffe, R. V., Lally, J. S., Fisher, R. M. 1973. Electron petrography of Apollo 14 and 15 breccias and shock-produced analogs. *Proc. Lunar Sci. Conf.*, 4th. *Geochim. Cosmochim. Acta* 1: Suppl. 4, pp. 365-82
- Compston, W., Berry, H., Vernon, M. J., Chappell, B. W., Kaye, M. J. 1971. Rubidium-strontium chronology and chemistry of lunar material from the Ocean of Storms. *Proc. Lunar Sci. Conf.*, 2nd. 2: 1471-85. Cambridge: M.I.T. Press
- Compston, W., Chappell, B. W., Arriens, P. A., Vernon, M. J. 1970. The chemistry and age of Apollo 11 lunar materials. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 2: Suppl. 1, pp. 1007-27
- Crawford, M. L. 1973. Crystallization of plagioclase in mare basalts. *Proc. Lunar Sci. Conf.*, 3rd. *Geochim. Cosmochim. Acta* 1: Suppl. 3, pp. 705-17
- Crawford, M. L., Hollister, L. S. 1974. KREEP basalt: A possible partial melt from the lunar interior. *Proc. Lunar Sci. Conf.*, 5th. *Geochim. Cosmochim. Acta* 1: Suppl. 5, pp. 399-419
- Dowty, E., Klaus, K., Prinz, M. 1974a. Lunar pyroxene-phyric basalts: Crystallization under supercooled conditions. *J. Petrol.* 15: 419-53
- Dowty, E., Prinz, M., Keil, K. 1973. Composition, mineralogy, and petrology of 28 mare basalts from Apollo 15 rake samples. *Proc. Lunar Sci. Conf.*, 4th. *Geochim. Cosmochim. Acta* 1: Suppl. 4, pp. 423-44
- Dowty, E., Prinz, M., Keil, K. 1974b. Ferroan anorthosite: a widespread and distinctive lunar rock type. *Earth Planet. Sci. Lett.* 24: 15-25
- Drake, M. J. 1975. The crystallization of plagioclase feldspar from silicate melt. *Lunar Science VI*, 199-201. Houston: Lunar Sci. Inst.
- Drake, M. J., Taylor, G. J., Goles, G. G. 1974. Descartes Mountains and Cayley Plains: composition and provenance. *Proc. Lunar Sci. Conf.*, 5th. *Geochim. Cosmochim. Acta* 2: Suppl. 5, pp. 991-1008

- Duncan, A. R., Erlank, A. J., Willia, J. P., Ahrens, L. H. 1973. Composition and inter-relationships of some Apollo 16 samples. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta 2: Suppl. 4*, pp. 1097-1113.
- El Goresy, A., Ramdohr, P., Medenbach, O., Bernhardt, H. 1974. Taurus-Littrow TiO_2 -rich basalts: Opaque mineralogy and geochemistry. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta 1: Suppl. 5*, pp. 627-52.
- Evensen, N., Murthy, V. R., Coscio, M. R. 1973. Rb-Sr ages of some mare basalts and the isotopic and trace element systematics in lunar fines. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta 2: Suppl. 4*, pp. 1707-24.
- Frondel, J. W. 1972. Harvard University preprint.
- Ganapathy, R., Keays, R. R., Laul, J. C., Anders, E. 1970. Trace elements in Apollo 11 lunar rocks: Implications for meteorite influx and origin of moon. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta 2: Suppl. 1*, pp. 1117-42.
- Gast, P. W. 1972. The chemical composition and structure of the moon. *Moon 4*: 630-57.
- Gay, P., Bown, M. G., Muir, I. D., Bancroft, G. M., Williams, P. G. L. 1971. Mineralogy and petrographic investigation of some Apollo 12 samples. *Proc. Lunar Sci. Conf., 2nd. 1*: 377-92. Cambridge: M.I.T. Press.
- Gibson, E. K., Hubbard, N. J., Wiesmann, H., Bansal, B. M., Moore, G. W. 1972. How to lose Rb, K, and change the K/Rb ratio: an experimental study. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta 2: Suppl. 3*, pp. 1263-73.
- Gooley, R., Brett, R., Warner, J. L., Smyth, J. R. 1974. A lunar rock of deep crustal origin: sample 76535. *Geochim. Cosmochim. Acta 38*: 1329-39.
- Green, D. H., Ringwood, A. E., Ware, N. G., Hibberson, W. O., Major, A., Kiss, E. 1971. Experimental petrology and petrogenesis of Apollo 12 basalts. *Proc. Lunar Sci. Conf., 2nd. Geochim. Cosmochim. Acta 1: Suppl. 2*, pp. 601-15.
- Green, D. H., Ringwood, A. E., Ware, N. G., Hibberson, W. O. 1975. Experimental petrology and petrogenesis of Apollo 17 mare basalts. *Lunar Science VI*, 311-13. Houston: Lunar Sci. Inst.
- Grieve, R. A. F., Plant, A. G., Dence, M. R. 1974. Lunar impact melts and terrestrial analogs: Their characteristics, formation, and implications for lunar crustal evolution. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta 1: Suppl. 5*, pp. 261-73.
- Grove, T. L., Walker, D., Longhi, J., Stolper, E. M., Hays, J. F. 1973. Petrology of rock 12002 from Oceanus Procellarum. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta 1: Suppl. 4*, pp. 995-1011.
- Haggerty, S. E. 1971. Compositional variations in lunar spinels. *Nature 233*: 156-60.
- Haggerty, S. E. 1972a. Subsolidus reduction of lunar spinels. *Nature 234*: 113-17.
- Haggerty, S. E. 1972b. Luna 16: An opaque mineral study and a systematic examination of compositional variations of spinels from Mare Fecunditatis. *Earth Planet. Sci. Lett.* 13: 328-52.
- Haggerty, S. E. 1973. Armalcolite and genetically associated opaque minerals in the lunar samples. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta 1: Suppl. 4*, pp. 777-97.
- Haskin, L. A., Allen, R. O., Helmke, P. A., Paster, T. P., Anderson, M. R., Korotev, R. L., Zweifel, K. A. 1970. Rare earths and other trace elements in Apollo 11 lunar samples. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta 2: Suppl. 1*, pp. 1213-31.
- Hollister, L. S., Trzcinski, W. E., Hargraves, R. B., Kulick, C. G. 1971. Petrogenetic significance of pyroxenes in two Apollo 12 samples. *Proc. Lunar Sci. Conf., 2nd 1*: 529-57. Cambridge: M.I.T. Press.
- Howard, K. A., Carr, M. H., Muehlberger, W. R. 1973. Basalt stratigraphy of southern Mare Serenitatis. In *Apollo 17 Prelim. Science Report, NASA SP-330*, Sect. 29, pp. 1-12.
- Hubbard, N. J., Gast, P. W., Rhodes, J. M., Bansal, B. M., Wiesmann, H., Church, S. E. 1972. Nonmare basalts: Part II. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta 2: Suppl. 3*, pp. 1161-79.
- Hubbard, N. J., Rhodes, J. M., Gast, P. W., Bansal, B. M., Shih, C., Wiesmann, H., Nyquist, L. E. 1973. Lunar rock types: The role of plagioclase in non-mare and highland rock types. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta 2: Suppl. 4*, pp. 1297-1312.
- James, O. B. 1972. Lunar anorthosite 15415: texture, mineralogy, and metamorphic history. *Science 175*: 432-34.
- James, O. B. 1974. Lunar highlands breccias generated by major impacts. *Proc. Sov. Am. Conf. Cosmochem. Moon Planets* (preprint).
- James, O. B., Wright, T. L. 1972. Apollo 11 and 12 mare basalts and gabbros: classification, compositional variations, and possible petrogenetic relations. *Geol. Soc. Am. Bull.* 83: 2357-82.
- Laul, J. C., Schmitt, R. A. 1973. Chemical

- composition of Apollo 15, 16 and 17 samples. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta* 2: Suppl. 4, pp. 1349-67.
- Laul, J. C., Wakita, H., Showalter, D. L., Boynton, W. V., Schmitt, R. A. 1972. Bulk, rare earth, and other trace elements in Apollo 14 and 15 and Luna 16 samples. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 2: Suppl. 3, pp. 1181-1200.
- Levinson, A. A., Taylor, S. R. 1971. *Moon Rocks and Minerals*. Oxford: Pergamon.
- Lofgren, G. E., Usselman, T. M., Donaldson, C. H. 1975. Cooling history of Apollo 15 quartz normative basalts determined from cooling rate experiments. *Lunar Science VI*, 515-17. Houston: Lunar Sci. Inst.
- Longhi, J., Walker, D., Grove, T. L., Stolper, E. M., Hays, J. F. 1974. The petrology of the Apollo 17 mare basalts. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 1: Suppl. 5, pp. 447-69.
- LSPET (Lunar Sample Preliminary Examination Team). 1972. The Apollo 15 lunar samples: A preliminary description. *Science* 175:363-75.
- LSPET (Lunar Sample Preliminary Examination Team). 1973. Preliminary examination of lunar samples. *Apollo 17 Preliminary Science Report, NASA SP-330*, Sect. 7, pp. 1-46.
- Metzger, A. E., Trombka, J. L., Peterson, L. E., Reedy, R. C., Arnold, J. R. 1973. Lunar surface radioactivity: preliminary results of the Apollo 15 and Apollo 16 gamma ray spectrometer experiments. *Science* 179:800.
- Metzger, A. E., Trombka, J. L., Reedy, R. C., Arnold, J. R. 1974. Elemental concentrations from lunar orbital gamma-ray measurements. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 2: Suppl. 5, pp. 1067-78.
- Morgan, J. W., Laul, J. C., Krahenbuhl, U., Ganapathy, R., Anders, E. 1972. Major impacts on the moon: characterization from trace elements in Apollo 12 and 14 samples. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 2: Suppl. 3, pp. 1377-95.
- Nava, D. F., Philpotts, J. A. 1973. A lunar differentiation model in light of new chemical data on Luna 20 and Apollo 16 soils. *Geochim. Cosmochim. Acta* 37: 963-73.
- Nunes, P. D., Tatsumoto, M., Unruh, D. M. 1974. U-Th-Pb systematics of some Apollo 17 samples. *Lunar Science V*, 562-64. Houston: Lunar Sci. Inst.
- Nyquist, L. E., Gast, P. W., Church, S. E., Wiesmann, H., Bansal, B. 1972. Rb-Sr systematics for chemically defined Apollo 15 materials. *The Apollo 15 Lunar Samples* 380-84. Houston: Lunar Sci. Inst.
- Papanastassiou, D. A., Wasserburg, G. J. 1970. Rb-Sr ages from the Ocean of Storms. *Earth Planet. Sci. Lett.* 8:269-78.
- Papanastassiou, D. A., Wasserburg, G. J., Burnett, D. S. 1970. Rb-Sr ages of lunar rocks from the Sea of Tranquillity. *Earth Planet. Sci. Lett.* 8:1-19.
- Papanastassiou, D. A., Wasserburg, G. J. 1972. Rb-Sr age of a Luna 16 basalt and the model age of lunar soils. *Earth Planet. Sci. Lett.* 13:368-74.
- Papike, J. J., Bence, A. E., Lindsley, D. H. 1974. Mare basalts from the Taurus-Littrow region of the moon. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 1: Suppl. 5, pp. 471-504.
- Philpotts, J. A. 1970. Redox estimation from a calculation of Eu^{2+} and Eu^{3+} concentrations in natural phases. *Earth Planet. Sci. Lett.* 9:257-68.
- Phinney, W. C., Warner, J. L., Simonds, C. H., Lofgren, G. E. 1972. Classification and distribution of rock types at Spur Crater. *The Apollo 15 Lunar Samples*, 149-53. Houston: Lunar Sci. Inst.
- Pieters, C., Head, J. W., McCord, T. B., Adams, J. B., Zisk, S. 1975. Geological and geochemical units of Mare Humorum: Further definition using remote sensing and lunar sample information. *Lunar Science VI*, 637-39. Houston: Lunar Sci. Inst.
- Prinz, M., Dowty, E., Keil, K. 1973a. A model for the origin of orange and green glasses and the filling of mare basins. *EOS. Trans. Am. Geophys. Union* 54: 605-6.
- Prinz, M., Dowty, E., Keil, K., Bunch, T. E. 1973b. Spinel troctolite and anorthosite in Apollo 16 samples. *Science* 179:74-76.
- Prinz, M., Dowty, E., Keil, K., Bunch, T. E. 1973c. Mineralogy, petrology and chemistry of lithic fragments from Luna 20 fines: origin of the cumulate ANT suite and its relationship to high-alumina and mare basalts. *Geochim. Cosmochim. Acta* 37:979-1006.
- Reid, A. M., Lofgren, G. E., Heiken, G. H., Brown, R. W., Moreland, G. 1973a. Apollo 17 orange glass, Apollo 15 green glass and Hawaiian lava fountain glass. *EOS. Trans. Am. Geophys. Union* 54: 606-7.
- Reid, A. M., Ridley, W. I., Donaldson, C., Brown, R. W. 1973b. Glass compositions in the orange and gray soils from Shorty Crater, Apollo 17. *EOS. Trans. Am. Geophys. Union* 54:607-8.

- Reid, A. M., Warner, J., Ridley, W. I., Johnston, D. A., Harmon, R. S., Jakes, P., Brown, R. W. 1972. The major element compositions of lunar rocks as inferred from glass compositions in the lunar soils. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 1: Suppl. 3, pp. 363-78.
- Reid, A. M., Warner, J. L., Ridley, W. I., Brown, R. W. 1973c. Luna 20 soil: abundance and composition of phases in the 45-125 micron fraction. *Geochim. Cosmochim. Acta* 37: 1011-1030.
- Rhodes, J. M., Hubbard, N. J. 1973. Chemistry, classification, and petrogenesis of Apollo 15 mare basalts. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta* 2: Suppl. 4, pp. 1127-48.
- Rhodes, J. M., Rodgers, K. V., Shih, C., Bansal, B. M., Nyquist, L. E., Wiesmann, H., Hubbard, N. J. 1974. The relationship between geology and soil chemistry at the Apollo 17 landing site. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 2: Suppl. 5, pp. 1097-1117.
- Ridley, W. I., Brett, R. 1973. Petrogenesis of basalt 70035: a multi-stage cooling history. *EOS. Trans. Am. Geophys. Union* 54: 611-12.
- Ringwood, A. E. 1974. Petrogenesis of maria basalts and composition of lunar interior. *EOS. Trans. Am. Geophys. Union* 55: 325 (Abstr.)
- Ringwood, A. E., Essene, E. 1970. Petrogenesis of Apollo 11 basalts, internal constitution and origin of the moon. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta*: Suppl. 1, pp. 769-99.
- Roedder, E., Weiblen, P. W. 1973. Origin of orange glass spherules in Apollo 17 sample 74220. *EOS. Trans. Am. Geophys. Union* 54: 612-13.
- Rose, H. J., Cuttitta, F., Ansell, C. S., Carron, M. K., Christian, R. P., Dwornik, E. J., Greenland, L. P., Ligon, D. T. 1972. Compositional data for twenty-one Fra Mauro lunar materials. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 2: Suppl. 3, pp. 1215-29.
- Rose, H. J., Cuttitta, F., Berman, S., Carron, M. K., Christian, R. P., Dwornik, E. J., Greenland, L. P., Ligon, D. T. 1973. Compositional data for twenty-two Apollo 16 samples. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta* 2: Suppl. 4, pp. 1149-58.
- Ross, M., Bence, A. E., Dwornik, E. J., Clark, J. R., Papike, J. J. 1970. Mineralogy of the lunar pyroxenes, augite and pigeonite. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 1: Suppl. 1, pp. 839-48.
- Shih, C., Wiesmann, H., Haskin, L. A. 1975. On the origin of high-Ti mare basalts. *Lunar Science VI*, 735-37. Houston: Lunar Sci. Inst.
- Simonds, C. H., Phinney, W. C., Warner, J. L. 1974. Petrography and classification of Apollo 17 non-mare rocks with emphasis on samples from the Station 6 boulder. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 1: Suppl. 5, pp. 337-53.
- Singer, S. F., Banderhmann, L. W. 1970. Where was the moon formed? *Science* 170: 438-39.
- Smith, J. V. 1971. Minor elements in Apollo 11 and Apollo 12 olivine and plagioclase. *Proc. Lunar Sci. Conf., 2nd. 1*: 143-50. Cambridge: M.I.T. Press.
- Smith, J. V., Anderson, A. T., Newton, R. C., Olsen, E. J., Wyllie, P. J., Crewe, A. V., Isaacson, M. S., Johnson, D. 1970. Petrologic history of the moon inferred from petrography, mineralogy, and petrogenesis of Apollo 11 rocks. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 1: Suppl. 1, pp. 897-925.
- Storey, W. C. 1974. Anomalous lunar plagioclase composition and the composition of coexisting melt. *Nature* 251: 403-5.
- Taylor, G. J. 1972. The composition of the lunar highlands: evidence from modal and normative plagioclase contents in anorthositic lithic fragments and glass. *Earth Planet. Sci. Lett.* 16: 263-68.
- Taylor, S. R. 1975. Lunar sciences, a post-Apollo view. Oxford: Pergamon.
- Taylor, S. R., Bence, A. E. 1975. Petrogenesis of the lunar highland crust. *Lunar Science VI*, 804-6. Houston: Lunar Sci. Inst.
- Taylor, S. R., Gorton, M. P., Muir, P., Nance, W. B., Rudowski, R., Ware, N. 1973. Composition of the Descartes region, lunar highlands. *Geochim. Cosmochim. Acta* 37: 2665-83.
- Taylor, S. R., Jakes, P. 1974. The geochemical evolution of the moon. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 2: Suppl. 5, pp. 1287-1305.
- Taylor, S. R., Kaye, M., Muir, P., Nance, W., Rudowski, R., Ware, N. 1972. Composition of the lunar uplands: chemistry of Apollo 14 samples from Fra Mauro. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 2: Suppl. 3, pp. 1231-49.
- Tera, F., Eugster, O., Burnett, D. S., Wasserburg, G. J. 1970. Comparative study of Li, Na, K, Rb, Cs, Ca, Sr and Ba abundances in achondrites and in Apollo 11 lunar samples. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 2: Suppl. 1, pp. 1637-57.

- Tera, F., Wasserburg, G. J. 1974. U-Th-Pb systematics on lunar rocks and inferences about lunar evolution and the age of the moon. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 2: Suppl. 5, pp. 1571-99
- Toksoz, M. N. 1974. Geophysical data and the interior of the moon. *Ann. Rev. Earth Planet. Sci.* 2: 151-77
- Walker, D., Longhi, J., Hays, J. F. 1972. Experimental petrology and origin of Fra Mauro rocks and soil. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta* 1: Suppl. 4, pp. 797-817
- Warner, J. L. 1971. Lunar crystalline rocks: petrology and geology. *Proc. Lunar Sci. Conf., 2nd.* 1: 469-80. Cambridge: M.I.T. Press
- Warner, J. L. 1972. Metamorphism of Apollo 14 breccias. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 1: Suppl. 3, pp. 623-43
- Warner, J. L., Simonds, C. H., Phinney, W. C. 1973. Apollo 16 rocks: classification and petrogenetic model. *Proc. Lunar Sci. Conf., 4th. Geochim. Cosmochim. Acta* 1: Suppl. 4, pp. 481-504
- Watkins, N. D., Haggerty, S. E. 1967. Primary oxidation variation and petrogenesis in a single lava. *Contrib. Mineral. Petrol.* 15: 251-71
- Weill, D. F., McCallum, I. S., Bottinga, Y., Drake, M. J., McKay, G. A. 1970. Mineralogy and petrology of some Apollo 11 igneous rocks. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 1: Suppl. 1, pp. 937-55
- Weill, D. F., McKay, G. A., Kridelbaugh, S. J., Grutzeck, M. 1974. Modelling the evolution of Sm and Eu abundances during lunar igneous differentiation. *Proc. Lunar Sci. Conf., 5th. Geochim. Cosmochim. Acta* 2: Suppl. 5, pp. 1337-52
- Williams, R. J. 1972. The lithification and metamorphism of lunar breccias. *Earth Planet. Sci. Lett.* 16: 250-56
- Willis, J. P., Erlank, A. J., Gurney, J. J., Theil, R. H., Ahrens, L. H. 1972. Major, minor, and trace element data for some Apollo 11, 12, 14 and 15 samples. *Proc. Lunar Sci. Conf., 3rd. Geochim. Cosmochim. Acta* 2: Suppl. 3, pp. 1269-73
- Wilshire, H. G., Stuart-Alexander, D. E., Jackson, E. D. 1973. Petrology and classification of the Apollo 16 samples. *Lunar Science IV.* 784-86. Houston: Lunar Sci. Inst.
- Wood, J. A. 1972. Thermal history and early magmatism in the moon. *Icarus* 16: 229-40
- Wood, J. A., Dickey, J. S., Marvin, U. B., Powell, B. N. 1970. Lunar anorthosites and a geophysical model of the moon. *Proc. Apollo 11 Lunar Sci. Conf. Geochim. Cosmochim. Acta* 1: Suppl. 1, pp. 965-88

On high-alumina mare basalts

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Abstract—Aluminous mare basalts have been found at several lunar sites, although they are not abundant. A group of crystalline clasts in breccia 14063 are also aluminous mare basalts with higher TiO_2 , Na_2O , Mg/Fe ratio and lower FeO than other aluminous mare basalts. Composition of ilmenite, clinopyroxene, and plagioclase confirm that crystallization took place from a melt with high TiO_2 and Mg/Fe. A review of ages and siderophile trace-element abundances for aluminous mare basalts, suggests they are not hybrid rocks produced by melting of a mare + terra rock mix, but are pristine igneous melts from the lunar interior. Consideration of rare-earth element abundances indicate the source for aluminous mare basalts is pyroxenitic, with variable clinopyroxene/orthopyroxene ratio, and is not significantly different from the source(s) of normal mare basalts.

INTRODUCTION

THE DISCOVERY of mare basalt clasts in Apollo 14 breccias (LSPET, 1971) raised the possibility that such basalts may have erupted on the lunar surface prior to 3.9 b.y. The largest clast 14053, an aluminous basalt distinctly different from the common low-alumina mare basalts, has been dated at 3.94 b.y. (Wasserburg *et al.*, 1972). Accepting the possibility that this sample is a melted aggregate of mare and terra material, the implication remains that mare volcanism began prior to 4 b.y. (Huneke *et al.*, 1972a,b). Similar arguments apply to the aluminous mare basalts in 14321 which have been dated at 3.95–4.05 b.y. (Mark *et al.*, 1973).

Complicating the picture are mare clasts with ages of 3.4–3.5 b.y. which suggest that there was substantial reworking of Fra Mauro breccias after their excavation at the onset of the Imbrian period. Such reworking might be reflected in a "third event" (Eratosthenian cratering?) postulated from Pb isotope data (Tatsumoto *et al.*, 1972). Impact ejection of basalt from any of the near mare to the Fra Mauro site probably required greater penetration than for the large samples collected from the mare surfaces. Hence the possibility is raised that mare basalt clasts in terra breccias represent deeper stratigraphic levels than samples collected upon the mare surfaces. In the absence of radiometric age determinations such clasts may reflect either pre-Imbrian period volcanism, or post-Imbrian reworking of the regolith.

In the broadest sense, two major-basalt "series" have been recognized from the mare basins; a series of titaniferous basalts (9–13% TiO_2 ; ~9% Al_2O_3) representing the earliest eruptions in Mare Tranquillitatis and Serenitatis; and a series of low-titanium basalts (1.5–3% TiO_2 ; ~9% Al_2O_3) from Oceanus Procellarum and Palus Putredinus. However, rare-aluminous mare basalts have been described as clasts in terra breccias (14053, 14072, 14321), in some mare breccias

(O'Hara *et al.*, 1974), and from Mare Fecunditatis soil. Reid and Jakeš (1974) initially drew attention to these anomalous basalt compositions (Table 1), which also form preferred compositions in glasses from mare soils. Doubt remains, however, that many of these aluminous compositions do not reflect *pristine* mare basalt, because of the unconfirmed supposition that mixing of aluminous highland material with common mare basalt, accompanied by impact melting, would produce hybrid rocks of aluminous mare basalt composition. However, aluminous basalt fragments from Luna 16 soil have generally been accepted as *pristine* basalt from Mare Fecunditatis, and there seems no *a priori* reason to assume all aluminous basalts are hybrid rocks.

In the present paper a small suite of aluminous mare clasts are described from 14063, a white medium-grade breccia collected on the rim of Cone Crater. Schonfeld and Meyer (1973) consider this and other white breccias to have originated from the deepest stratigraphic level within Cone Crater, and represent ejecta from the Imbrium Basin. The clasts have a uniform texture defined by lathy to aciculate plagioclase, lathy and anhedral ilmenite, intergranular pyroxene, and rare pale-brown mesostasis glass (Fig. 1). The texture suggests rapid cooling from a silicate melt in which plagioclase and ilmenite nucleated prior to pyroxene crystallization. Analyses have been made of major mineral phases, together with some ion microprobe data collected for trace elements in plagioclases. Comparison is made with similar data collected from other plagioclases in 14063. The overall petrologic information suggests the existence of an aluminous mare basalt melt unlike those previously described. Mixing models suggest such a melt was not a hybrid combination of terra and mare rocks.

Table 1. Major-element chemistry of aluminous mare basalts.

	1	2	3	4	5	6	7	8
SiO ₂	45.9	45.2	46.3	46.82	45.50	43.80	40.2	43.7
TiO ₂	7.3	2.57	2.79	2.33	4.04	4.90	7.2	3.3
Cr ₂ O ₃	0.2	0.51	0.37	0.32		0.28		
Al ₂ O ₃	14.4	11.1	13.7	13.81	13.95	13.65	13.2	13.2
MnO				0.26	0.26	0.20		
FeO	10.7	17.8	17.0	15.92	17.77	19.35	16.5	16.5
MgO	6.7	12.2	8.54	6.30	5.95	7.05	8.5	9.9
CaO	11.3	9.84	11.2	11.57	11.96	10.40	12.0	11.1
Na ₂ O	1.0	0.32	0.44	0.80	0.63	0.38	0.3	0.2
K ₂ O	0.1	0.08	0.11	0.25	0.21	0.15	0.10	0.16

- (1) Average composition of basaltic clasts in 14063, broad beam analysis.
- (2) XRF analysis of 14072, Hubbard *et al.* (1972).
- (3) XRF analysis of 14053, Hubbard *et al.* (1972).
- (4) Average 7 vitrophyric and variolitic clasts, 14321, Grieve *et al.* (1975).
- (5) Basalt fragment in Luna 16 soil, Albee *et al.* (1972).
- (6) Luna 16 basalt, Vinogradov *et al.* (1971).
- (7), (8). Preferred glass compositions in Apollo 11, and 12 soils, respectively, Reid *et al.* (1972).

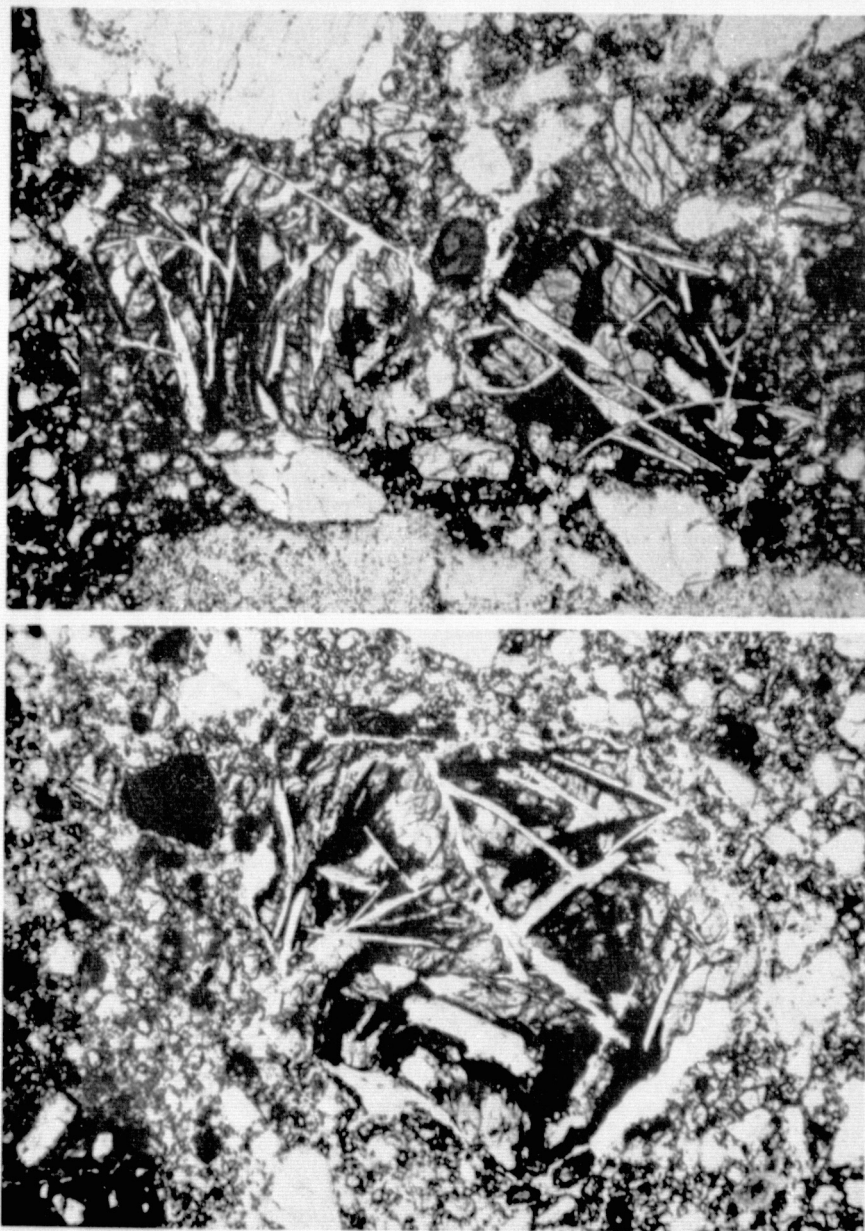


Fig. 1. Aluminous mare clasts in breccia 14063. Note the acicular form of plagioclase and ilmenite. Mutually intergrown crystals suggest plagioclase and ilmenite may have nucleated prior to pyroxene.

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Broad beam analyses of these clasts, averaged in Table 1, indicates their unique major-element chemistry, distinctive from both low-alumina and aluminous mare basalts. However, the bulk chemistry is consistent with the observed early crystallization of plagioclase and ilmenite, in that the melt was enriched in both TiO_2 and Al_2O_3 . Other notable features are the high-Mg/Fe ratio, Na_2O content and low-FeO concentration compared to the common iron-rich mare basalts.

Microprobe analyses of the major-mineral phases also support crystallization from a melt enriched in TiO_2 , Na_2O , and with a high-Mg/Fe ratio. Anhedral ilmenite contains a maximum of 7.2% MgO (Table 2), forming on ilmenite-geikielite solid solution, whereas acicular ilmenites have about 5.6% MgO. High-Mg ilmenites are not common in low-titanium mare basalts, although some have been reported (El Goresy *et al.*, 1971). They are however ubiquitous in titaniferous mare basalts, where they may be a product of an armalcolite-liquid reaction (Haggerty, 1972). Ilmenite produced in this manner may contain an excess of titanium (Haggerty, 1973), as observed for the larger, Mg-rich ilmenites here. Such an excess is not observed for the bladed ilmenites. Experimental studies suggest, however, that armalcolite crystallizes stably only for $\sim 30^\circ\text{C}$ below its liquidus temperature (Green *et al.*, 1975), and for fast cooling rates, such as texturally inferred for these basalts, complete reaction of armalcolite would not occur (Usselman *et al.*, 1975). Alternately, the Mg-ilmenites may have crystallized as a result of a high-Mg activity within the melt, as inferred

Table 2. Microprobe analyses of oxide phases in 14063 basalts.

	1	2	3
TiO_2	56.18	56.37	54.44
Al_2O_3	0.08	0.10	0.14
Cr_2O_3	0.56	0.47	0.59
FeO	35.46	35.94	38.25
MnO	0.34	0.39	0.38
MgO	7.17	6.99	5.65
Total	99.79	100.26	99.45
Structural formulae (12 oxygens)			
Ti	4.02	4.03	3.98
Al	0.01	0.01	0.02
Cr	0.04	0.04	0.05
Fe	2.82	2.85	3.11
Mn	0.03	0.03	0.03
Mg	1.02	0.99	0.82

(1), (2). Larger, anhedral ilmenites.

(3). Acicular ilmenite.

from the bulk composition, without prior crystallization of armalcolite. Indeed Usselman *et al.* (1975) indicate that titaniferous, aluminous mare basalts do not crystallize armalcolite prior to ilmenite. Hence the Mg-ilmenites probably crystallized in response to the high-Mg/Fe ratio of the basaltic melt.

The initial pyroxene to crystallize was a calcic pigeonite (Table 3, Fig. 2). The calcium-poor composition probably resulted from a competition for calcium between pyroxene and plagioclase. Most Al/Ti ratios in core pigeonite have Al/Ti=2:1, suggesting coprecipitation of early pigeonite and plagioclase (Bence and Papike, 1972), although this ratio appears to be sensitive to the physical proximity of plagioclase and pigeonite during crystallization, i.e. local variations in chemical gradients within the melt. Core pigeonite contains a maximum of 1% Cr₂O₃. Occasional analyses suggest the presence of very minor Al^{VI} at an early stage in the crystallization history, followed by a rapid change to Al/Ti < 2:1 reflecting the presence of either or both R²⁺Ti³⁺SiAlO₆ and R²⁺Cr²⁺Si₂O₆ components.

Pyroxene crystallization progressed from calcic pigeonite to augite and finally

Table 3. Microprobe analyses of pyroxenes in 14063 basalts.

	1	2	3	4	5	6	7
SiO ₂	47.27	48.28	48.55	48.06	48.18	48.23	48.44
TiO ₂	4.12	3.83	4.19	2.40	3.04	2.81	2.36
Al ₂ O ₃	5.24	3.72	3.07	2.90	4.51	3.65	1.99
Cr ₂ O ₃	1.05	0.81	0.68	0.29	0.49	0.40	0.16
FeO	13.14	12.31	11.78	18.17	12.33	14.30	23.14
MnO	0.17	0.18	0.17	0.30	0.17	0.21	0.21
MgO	16.97	14.85	13.94	11.37	13.67	13.73	8.69
CaO	11.66	14.43	16.39	15.50	16.80	15.37	14.84
Na ₂ O	0.09	0.05	0.05	0.05	0.03	0.02	0.02
Total	99.71	98.66	98.82	99.04	99.22	98.72	99.85
Structural formulae (6 oxygens)							
Si	1.769	1.836	1.843	1.869	1.825	1.846	1.905
Ti	0.116	0.109	0.119	0.070	0.086	0.081	0.069
Al	0.231	0.166	0.137	0.133	0.201	0.165	0.092
Cr	0.031	0.024	0.020	0.008	0.014	0.012	0.005
Fe	0.411	0.390	0.373	0.591	0.390	0.457	0.761
Mn	0.005	0.005	0.005	0.009	0.005	0.006	0.006
Mg	0.946	0.838	0.788	0.659	0.771	0.783	0.509
Ca	0.467	0.585	0.666	0.645	0.681	0.630	0.625
Na	0.006	0.003	0.003	0.003	0.002	0.001	0.001
Z	2.000	2.000	1.980	2.000	2.000	2.000	1.997
Fe/Mg	0.43	0.46	0.47	0.89	0.51	0.58	1.49
Al/Si	0.13	0.09	0.07	0.07	0.11	0.09	0.05
Al ^{VI}	—	0.002	—	0.002	0.026	0.011	—

(1)–(4). Core to rim of single crystal.

(5)–(7). Core to rim of single crystal.

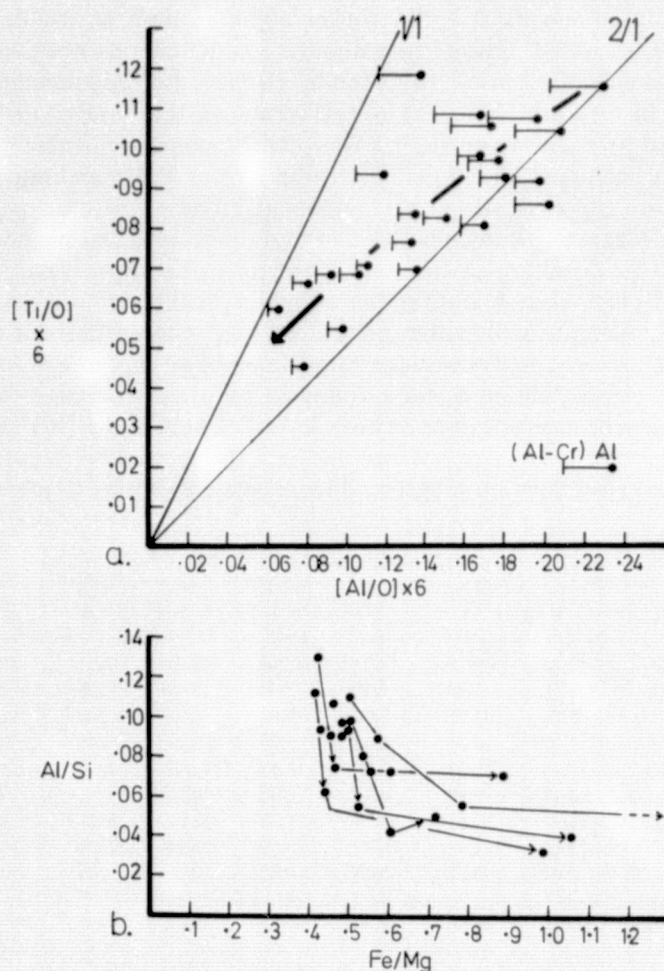


Fig. 2. (a) Ti-Al relations in mare pyroxenes from 14063. Core pyroxenes have high-Ti, Al contents close to the $Al/Ti = 2:1$ line but most grains have $Al/Ti < 2:1$. Bars represent removal of an $RCrSiAlO_6$ component. (b) Variations in Al/Si ratio of pyroxenes with increasing Fe/Mg ratio. Lines represent trends in individual grains. Note the initial sharp drop in Al/Si ratio, similar to that observed in Apollo 11 basalts, and other mare basalts with high-Ti/Al bulk ratios.

ferro-augite (Fig. 2). The overall compositional variation is much less than observed in most mare basalts, but compatible with fast cooling. The most notable feature of the pyroxenes is the high content of Ti, Al (Table 3), comparable to values observed in titaniferous basalts, but much higher than found in titanium-poor mare basalts. They differ however, from titaniferous basalt pyroxenes in the rapid deviation of Al/Ti ratios to below 2:1, suggesting rather more reducing crystallization conditions (Bence and Papike, 1972).

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Table 4. Analyses of plagioclase in 14063 basalts.

	1	2	3	4	5						
SiO ₂	47.93	47.83	49.11	48.90	51.17	Li	32	36	40	68	51
Al ₂ O ₃	33.13	32.90	31.79	32.29	30.14	Ba	139	120	168	179	457
FeO	0.33	0.40	0.45	0.53	0.57	Sr	228	280	274	420	437
MgO	0.38	0.35	0.43	0.33	0.26	Ti	474	375	520	682	726
CaO	16.66	15.96	15.27	14.88	14.08	Na ₂ O%	1.98	2.24	2.36	2.76	2.92
Na ₂ O	1.79	1.77	2.38	2.59	2.97						3.16
K ₂ O	0.18	0.10	0.16	0.32	0.36						
An%	81	79	75	73	67						
FeO/FeO + MgO	0.46	0.53	0.52	0.62	0.70						

Major-element analysis by electron microprobe. Trace-element analysis by ion microprobe using technique outlined in Meyer *et al.* (1974). Values used for Lake County standard plagioclase are: Li 4.1 ppm, Sr 582 ppm, Ba 63 ppm, Ti 230 ppm. Na₂O values with trace elements are ion probe data.

The initial *plagioclase* to crystallize was bytownite (An_{81}) zoned progressively to An_{67} . Notable here is the sodic nature of the liquidus *plagioclase* which is some 7–10-mole% An less than liquidus *plagioclase* in titaniferous mare basalts. The Mg/Fe ratios are high compared to *plagioclases* of similar An content in mare basalts, although precise comparisons would require detailed knowledge of the other Fe , Mg -bearing crystallizing with *plagioclase*. Nonetheless, the qualitative implication remains that Fe , Mg distribution in the *plagioclase* reflect a melt with high- Mg/Fe ratio, and higher Na_2O content than titaniferous mare basalts.

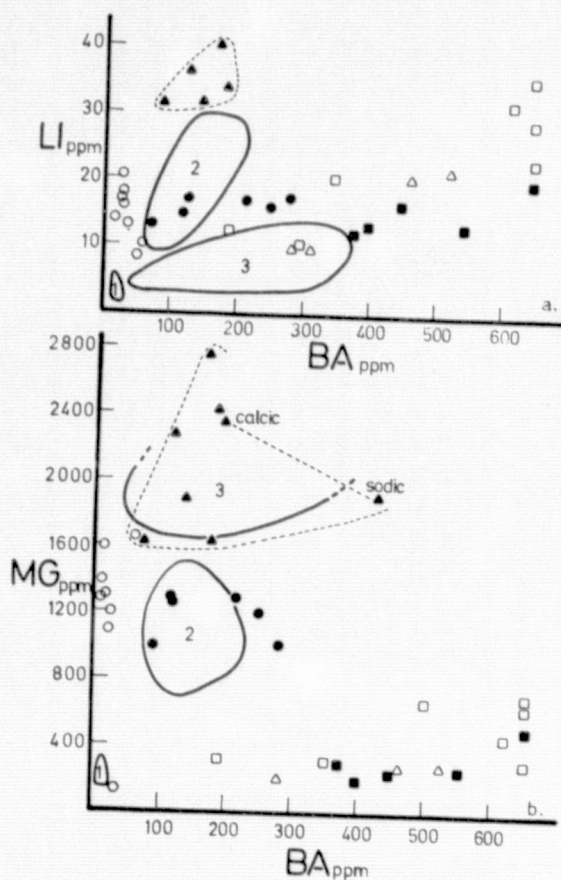


Fig. 3. (a) Li-Ba relationships in mare plagioclases from 14063 (filled triangles) as determined by ion microprobe. Fields labeled 1, 2, and 3 are spread of Li, Ba values in plagioclases from anorthosites, crystalline KREEP, and mare basalts, respectively. Included for comparison are data obtained by the author for crystalline low-alkali KREEP (circles), KREEP (filled circles), plagioclase rimming pink spinel (polygon), cataclastic anorthosite (triangles), single-plagioclase clasts (squares), and poikilitic clasts (filled squares). (b) Mg-Ba relations in mare plagioclases from 14063, and other fragments in Apollo 14 breccias. Symbols and fields as in (a). The dashed line joins calcic and sodic plagioclase analysis from the same clast, but not from a single-zoned crystal.

Ion microprobe data for Li, Mg, Ti, Ba, and Sr have also been obtained for plagioclase from these mare fragments as shown in Table 4. The acicular plagioclases provide analytical difficulties with a 20- μ diameter ion beam, and some of the high Li values (>40 ppm) measured correspond to areas that may have included some Mg-pyroxene. Only those analyses unequivocally from plagioclases are reported here. Meyer *et al.* (1974) have reported ion probe data, using the same instrument, for these trace elements in terra and mare plagioclases, and recognize several plagioclase groupings. In the present study, plagioclases were also analyzed from a number of terra clasts, their trace-element abundances falling within the general groupings erected by Meyer *et al.* (1974). Details of these studies will be reported elsewhere, but it is noteworthy that there is a consistency in ion probe data between different groups of analysts. Data for the mare plagioclases and terra plagioclases are shown in Figs. 3a and 3b. Ba and Sr contents are comparable with other mare plagioclase, whereas Li and some Mg values are higher (Fig. 3a), even outside the range found for KREEP basalts.

ALUMINOUS MARE BASALTS AS HYBRIDS

The thoroughly documented lunar process of mixing and remelting may be responsible for the aluminous nature of some mare-like basalts if aluminous terra rocks became mixed with mare basalt and remelted. Indeed the presence of a component of terra material in all mare soil testifies to the authenticity of the mixing process. Since mixing on the lunar surface is achieved by multiple meteorite bombardment, the identification of hybrid rocks produced by this process, usually relies upon anomalously high siderophile-element concentrations. The most striking example of this procedure, 14310, shows siderophile-element concentrations equivalent to lunar soils (Morgan *et al.*, 1972), and is generally accepted as an impact melt. It would, therefore, seem useful to examine some siderophile-element concentrations in aluminous mare basalts. Ir, Re, Au, and Ni concentrations in 14053 are similar to those found in mare basalts from Apollo 11, 12, and 15 but more than an order of magnitude less abundant than in lunar soils. Consistent data are less easily obtained for 12038 (Morgan *et al.*, 1972; Baedeker *et al.*, 1972), but generally the level of siderophile-element concentration is higher than for Oceanus Procellarum mare basalts. Although the lunar soils are greatly enriched in siderophiles relative to 12038, there remains some reason to suspect that this sample is slightly contaminated with a meteoritic component and may be hybrid. No precise measurements of siderophile elements have been published for aluminous basalts from Luna 16. Papanastassiou and Wasserburg (1972) have carried out Rb-Sr systematics for one Luna 16 aluminous basalt (Albee *et al.*, 1972), the Rb/Sr ratio being about half that found in the soil. Unless significant Rb loss has occurred, this basalt cannot represent remelted Luna 16 soil.

Aluminous mare basalts are abundant in breccia 14321 (Duncan *et al.*, 1975) and one example has been analyzed by Morgan *et al.* (1975) who note the

uniformly low concentrations of siderophile elements, very similar to those found in 14053 and common mare basalts.

Although some aluminous mare basalts have major-element compositions similar to mare soils e.g. 14053 is similar to a typical Apollo 12 soil, the measured ages appear incompatible with simple regolith melting. The alternative would be to postulate, in some cases, that well-mixed mare soils had already developed at ~ 4 b.y.

Apart from the marginal case of 12038, other aluminous mare basalts that have been suitably studied, encourage the conclusion that they are not polymict mixtures that have been remelted into hybrids. The clasts in 14063 cannot easily be modeled by any reasonable mixing of mare and highland material, in particular it is difficult to generate low-FeO values without increasing Al_2O_3 above the observed level, and also difficult to generate the relatively high- Na_2O value. The latter might be produced if an aluminous mare melt equilibrated with a residue containing plagioclase.

ALUMINOUS MARE BASALTS IN A FRAMEWORK OF LUNAR EVOLUTION

Trace-element considerations

Lithophile trace-element data have been reported for 14072 (Taylor *et al.*, 1972), 14053 (Hubbard *et al.*, 1972; Church *et al.*, 1972) a Luna 16 basalt (Philpotts *et al.*, 1972), and several basalt clasts from 14321 (Taylor *et al.*, 1972; Duncan *et al.*, 1975). All these basalts are characterized by negative Eu anomalies, the most extensive being for 14321 basalts, and least for 14072. Enrichment factors for REE vary from 30–60 over chondritic abundances, and most samples show a slight fractionation of light over heavy rare earths. Rb/Sr ratios are low, the highest ratio being .048 for a 14321 basalt clast. Rb/Sr and Zr/Hf ratios are within the range shown for mare basalts.

The lithophile trace-element abundances are frequently useful indicators of petrogenetic processes in lunar and terrestrial basalts, particularly in evaluating the chemistry of the source regions for basalts. Some constraints can be placed on the source region for mare basalts based upon rare-earth abundances, using the approach and data base of Weill *et al.* (1974). In past discussions it has generally been assumed that plagioclase plays an essential role in the formation of aluminous mare basalts (Philpotts *et al.*, 1972; Reid and Jakeš, 1974), in particular that they may represent partial melt products from a plagioclase-bearing source located between a pyroxenitic mantle and anorthositic crust (Jakeš *et al.*, 1972; Reid and Jakeš, 1974).

In Fig. 4 various mineralogies have been calculated for solid residues in equilibrium with aluminous basalt liquids under conditions of incipient equilibrium melting (Weill *et al.*, 1974). These calculations are determined by Sm and Eu abundances in aluminous mare basalts and by the trace-element characteristics of the source region. In Fig. 4 melting is evaluated for a source containing $5\times$, $10\times$ unfractionated chondritic abundances, sources with positive and negative Eu

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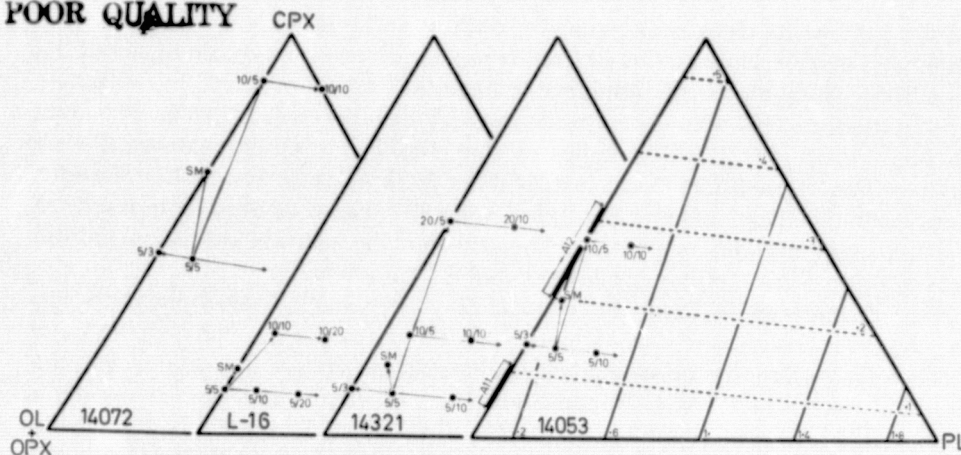


Fig. 4. Evaluation of the mineralogy of solid residues, assumed to be some combination of olivine + orthopyroxene + clinopyroxene + plagioclase, in equilibrium with various aluminous mare basalts. The equilibrium melting equation used is $C/Co = [F + \bar{D}(1 + F)]^{-1}$ as discussed by Weill *et al.* (1974), and is evaluated for Sm and Eu. The condition of incipient melting ($F = 0$) is assumed, although small degrees of melting do not drastically change the plotted points. The grid in the right triangle represents $\bar{D}$ (average distribution coefficient) for Eu (solid lines) and Sm (dashed lines), based upon the experimentally determined coefficients listed in Weill *et al.* (1974). Residual mineralogy is evaluated for various abundances of Sm, Eu in the residues e.g. 5/5 denoted 5 × chondritic abundances of Sm, Eu in the residue. The range of solidus assemblages in equilibrium with Apollo 11 and 12 mare basalts are shown on the right triangle, by assuming a source with a defined negative Eu anomaly. SM represents the composition of the source of mare basalts deduced by Taylor *et al.* (1974).

anomalies, and a source for mare basalts deduced by Taylor and Jakeš (1974). A number of interesting conclusions may be drawn from these data. In all cases, sources with significant positive Eu anomalies must equilibrate partial melts with about 15% or more plagioclase in order to develop negative Eu anomalies. In the case of 14072 the source had a maximum of about 10 × chondritic abundances, but would be composed almost entirely of clinopyroxene. More reasonable mineralogies are associated with lower initial abundances, involving cpx + opx + olivine ± minor plagioclase.

In all cases, the rare-earth abundances in aluminous mare basalts can be derived from sources not involving plagioclase if the source already has a minor Eu anomaly e.g. 14072, 14321, Luna 16, or from unfractionated source regions containing < 10%, and frequently < 5% plagioclase. The mineralogy of the source region may also be changed dramatically by varying the elemental abundances, and in general derivation from lithophile-element enriched sources requires equilibration with progressively larger amounts of clinopyroxene and plagioclase. It is important to note however that the low-Rb/Sr ratios observed for these basalts would not be consistent with partial melting of a highly enriched source.

Similar arguments have been made for mare basalts. It is clear, however, that aluminous mare basalts can be derived from source regions containing about 5× chondritic abundances of lithophile elements, and dominated by olivine + orthopyroxene. This would be consistent with high-pressure experimental data (Walker *et al.*, 1972) which indicates that 14072 is multiply saturated with olivine + opx at pressures equivalent to about 200 km depth. The lack of liquidus plagioclase in these experiments also suggests that a source composed of ol + opx + cpx and with an already defined Eu anomaly would be more appropriate than ol + cop + cpx + minor plagioclase and no Eu anomaly.

The differences in lithophile-element chemistry may be accounted for by varying the modal proportions of minerals in the source region, whilst maintaining a relatively constant level of elemental abundances. Hence the sequence Luna 16-14321-14053-14072 would represent a sequence involving progressively more clinopyroxene over olivine + orthopyroxene. It is also evident that mineralogically the sources of aluminous mare basalts are not significantly different from the sources of the common mare basalts.

Physiochemical source conditions

In the absence of precise experiments on aluminous mare basalts at elevated temperatures and pressures, estimates of the conditions under which these basalts developed are little better than speculations. At present, trace-element data provide the best restraints on source composition, the major-element data almost no restraints at all. Age data also suggest that formation of aluminous mare basalts was not a unique event, but occurred over a period of at least 0.5 b.y. During this time the lunar lithosphere became gradually thicker and the zone of incipient melting moved to progressively higher pressures. Hence it seems unlikely that pressure effects were significantly important in the generation of aluminous mare basalts, unlike the terrestrial situation for the production of aluminous basalts (Green *et al.*, 1967).

If aluminous mare basalts are primitive liquids, then slight chemical changes in the lunar mantle, which undoubtedly is laterally chemically heterogeneous, may be a more important consideration. Some possibilities are (a) slight differences in silica activity of the bulk upper mantle. The partitioning of Al_2O_3 , and hence TiO_2 into Ca-rich clinopyroxene is sensitive to SiO_2 activity, a slight increase in silica activity in a mantle composed of olivine + low-Ca pyroxene + calcic clinopyroxene would result in a stronger partitioning of alumina into the liquid phase upon partial melting. Such an effect might be important in a mantle showing variations in olivine/low-Ca pyroxene ratio (Akella and Boyd, 1973). (b) For source regions containing minor plagioclase and in which liquids equilibrated with olivine + low-Ca pyroxene + calcic pyroxene, the amount of ilmenite present, and the Fe/Mg ratio of the source partly determine the cotectic equilibrium relative to plagioclase and produce liquids with varying amounts of alumina. (c) Shift of cotectic equilibrium as a result of variable redox conditions. (d) The presence of minor aluminous phases, other than plagioclase, e.g. melilite.

Alternately, aluminous mare basalts may be residual liquids following fractionation of a more primitive mare basalt magma. Experimental evidence suggests that 12038 (Biggar *et al.*, 1971), 14072 (Walker *et al.*, 1972) and aluminous clasts in Apollo 11 breccias (O'Hara, 1974) are all cotectic liquids. In these cases the high-alumina content may result from extraction of low-alumina ferromagnesian phases, e.g. olivine, from a more normal mare basalt liquid. During this process, lithophile trace elements may be slightly enriched but the relative abundances hardly effected.

CONCLUSIONS

(1) The spectrum of aluminous mare basalts shows that most are low-titania types that are most similar to Apollo 12 and 15 basalts in terms of major-element abundances. However, preferred compositions amongst glass data, together with an enigmatic number of holocrystalline clasts in breccia 14063, suggest that aluminous mare basalts can have high-titania contents.

(2) Examination of siderophile-element concentrations shows that most aluminous mare basalts are not contaminated with a meteorite component and cannot be considered well-mixed hybrid rocks. They are pristine melts from the lunar interior.

(3) Sm and Eu abundances may be utilized to evaluate possible source regions for these aluminous basalts. Ultramafic sources involving principally olivine + orthopyroxene and variable amounts of clinopyroxene are indicated. Small amounts of plagioclase may also be tolerated, depending upon assumptions regarding Eu distributions. However, more than 10–15% plagioclase requires that the source have a marked positive Eu anomaly.

(4) In terms of lithophile trace elements, the sources for aluminous mare basalts are similar to the common mare basalts, and probably represent ultramafic upper mantle material.

(5) Silica activity, amount of ilmenite, and redox conditions, in the source may be important parameters in determining the alumina contents of mare basalts.

(6) The relative abundances of different rock groups returned from the moon can hardly be used to evaluate their importance in lunar evolution. The almost total lack of a third dimension in sampling effectively insures the verity of this statement. Terrestrial experience also tells us that the terminal stages of igneous activity frequently grossly misrepresent, in a chemical sense, the major stages of activity. Can this also be so in the mare basins where we have sampled only the surface veneer? As long as such a suspicion remains, the search for and study of chemically distinctive mare basalts remains fully warranted.

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REFERENCES

- Akella J. and Boyd F. R. (1973) Partitioning of Ti and Al between coexisting silicates, oxides, and liquids. *Proc. Lunar Sci. Conf. 4th*, p. 1049-1059.
- Albee A. L., Chodos A. A., Gangarz A. J., Haines E. L., Papanastassiou D. A., Ray L., Tera F., Wasserburg G. J., and Wen T. (1972) Mineralogy, petrology and chemistry of Luna 16 basaltic fragment B-1. *Earth Planet. Sci. Lett.* **13**(2) 353-367.
- Baedecker P. A., Chou C. L., and Wasson J. T. (1972) The extralunar component in lunar soils and breccias. *Proc. Lunar Sci. Conf. 3rd*, p. 1343-1359.
- Bence A. E. and Papike J. J. (1972) Pyroxenes as recorders of lunar basalt petrogenesis: Chemical trends due to crystal-liquid interactions. *Proc. Lunar Sci. Conf. 3rd*, p. 431-469.
- Church S. E., Bansal B. M., and Wiesmann H. (1972) The distribution of K, Ti, Zr, U and Hf in Apollo 14 and 15 materials. In *The Apollo 15 Lunar Samples* (editors J. W. Chamberlain and C. Watkins), p. 210-212. The Lunar Science Institute, Houston.
- Duncan A. R., McKay S. M., Stoesser J. W., Lindstrom M. M., Lindstrom D. J., Fruchter J. S., and Goles G. G. (1975) Lunar polymict breccia 14321: A compositional study of its principal components. *Geochim. Cosmochim. Acta* **39**, 247-260.
- El Goresy A., Randohr P., and Taylor L. A. (1971) The opaque minerals in the lunar rocks from Oceanus Procellarum. *Proc. Lunar Sci. Conf. 2nd*, p. 219-235.
- Gast P. W., Hubbard N. J., and Wiesmann, H. (1970) Chemical composition and petrogenesis of basalts from Tranquility Base. *Proc. Apollo 11 Lunar Sci. Conf.*, p. 1143-1163.
- Green T. H., Green D. H., and Ringwood A. E. (1967) The origin of high-alumina basalts and their relationships to quartz tholeiites and alkali basalts. *Earth Planet. Sci. Lett.* **2**(1), 41-51.
- Green D. H., Ringwood A. E., Ware N. G., and Hibberson W. O. (1975) Experimental petrology and petrogenesis of Apollo 17 mare basalts (abstract). In *Lunar Science VI*, p. 311-313. The Lunar Science Institute, Houston.
- Grieve R. A., McKay G. A., Smith H. D., and Weill D. F. (1975) Lunar polymict breccia 14321: A petrographic study. *Geochim. Cosmochim. Acta* **38**(3), 229-245.
- Haggerty S. E. (1972) Luna 16: An opaque mineral study and a systematic examination of compositional variations of spinels from Mare Fecunditatis. *Earth Planet. Sci. Lett.* **13**(2), 328-352.
- Haggerty S. E. (1973) Armalcolite and genetically associated opaque minerals in the lunar samples. *Proc. Lunar Sci. Conf. 4th*, p. 777-797.
- Hubbard N. J. and Gast P. W. (1971) Chemical composition and origin of nonmare lunar basalts. *Proc. Lunar Sci. Conf. 2nd*, p. 999-1020.
- Hubbard N. J., Gast P. W., Rhodes J. M., Bansal B. M., Weismann H., and Church S. E. (1972) Nonmare basalts: Part II. *Proc. Lunar Sci. Conf. 2nd*, p. 1161-1179.
- Huneke J. C., Podosek F. A., Turner G., and Wasserburg G. J. (1972a) ^{40}Ar - ^{39}Sr systematics in lunar rocks and separated minerals of lunar rocks from Apollo 14 and 15 (abstract). In *Lunar Science III*, p. 413-414. The Lunar Science Institute, Houston.
- Huneke J. C., Podosek F. A., and Wasserburg G. J. (1972b) Gas retention and cosmic rays exposure ages of a basalt fragment from Mare Fecunditatis. *Earth Planet. Sci. Lett.* **13**(2), 375-383.
- Jakeš P., Warner J., Ridley W. I., Reid A. M., Harmon R. S., Brett R., and Brown R. W. (1972) Petrology of a portion of the Mare Fecunditatis regolith. *Earth Planet. Sci. Lett.* **12**(2), 257-271.
- LSPET (1971) Preliminary examination of lunar samples from Apollo 14. *Science* **173**, 681-693.
- Mark R. K., Lee-Hu C., and Wetherill G. W. (1975) More on Rb-Sr in 14321 (abstract). In *Lunar Science VI*, p. 552-554. The Lunar Science Institute, Houston.
- Merrill R. B., Williams R. J., and Akella J. (1975) The system anorthite-forsterite-fayalite-silica to 2 kilobars with lunar petrologic implications (abstract). In *Lunar Science VI*, p. 557-559. The Lunar Science Institute, Houston.
- Meyer C., Anderson D. H., and Bradley J. G. (1974) Ion microprobe mass analysis of plagioclase from "nonmare" lunar samples. *Proc. Lunar Sci. Conf. 5th*, p. 685-706.
- Morgan J. W., Laul F. C., Krahenbuhl U., Ganapathy R., and Anders E. (1972) Major impacts on the moon: Characterization from trace elements in Apollo 12 and 14 samples. *Proc. Lunar Sci. Conf. 3rd*, p. 1377-1395.

- Morgan J. W., Ganapathy R., and Krahenbuhl W. (1975) Meteoritic trace elements in lunar rock 14321, 184. *Geochim. Cosmochim. Acta* 39(3), 261-264.
- O'Hara M. J., Biggar G. M., Hill P. G., Jefferies B., and Humphries D. J. (1974) Plagioclase saturation in lunar high-titanium basalt. *Earth Planet. Sci. Lett.* 21, 253-268.
- Papanastassiou D. A. and Wasserburg G. J. (1972) Rb-Sr age of a Luna 16 basalt and the model age of lunar soils. *Earth Planet. Sci. Lett.* 13(2), 368-374.
- Philpotts J. A. and Schnetzler C. C. (1970) Apollo 11 lunar samples: K, Rb, Sr, Ba and rare-earth concentrations in some rocks and separated phases. *Proc. Apollo 11 Lunar Sci. Conf.*, p. 1471-1486.
- Philpotts J. A., Schnetzler C. C., Nava D. F., Bottino M. L., Fullager P. D., Thomas H. H., Schuhmann S., and Kouns C. W. (1972) Apollo 14: Some geochemical aspects. *Proc. Lunar Sci. Conf. 3rd*, p. 1293-1305.
- Reid A. M., and Jakeš P. (1974) Luna 16 revisited: The case for aluminous mare basalts (abstract). In *Lunar Science V*, p. 627-629. The Lunar Science Institute, Houston.
- Reid A. M., Warner J., Ridley W. I., Johnston D. A., Harmon R. S., Jakeš P., and Brown R. W. (1972) The major element compositions of lunar rocks as inferred from glass compositions in the lunar soils. *Proc. Lunar Sci. Conf. 3rd*, p. 363-378.
- Schnetzler C. C. and Philpotts J. A. (1971) Alkali, alkaline earth, and rare-earth element concentrations in some Apollo 12 soils, rocks and separated phases. *Proc. Lunar Sci. Conf. 2nd*, p. 1101-1122.
- Schonfeld E. and Meyer J. C. (1973) The Old Imbrium Hypothesis. *Proc. Lunar Sci. Conf. 4th*, p. 125-138.
- Tatsumoto M., Hedge C. E., Doe B. R., and Umruh D. M. (1972) U-Th-Pb and Rb-Sr measurements on some Apollo 14 lunar samples. *Proc. Lunar Sci. Conf. 3rd*, p. 1531-1555.
- Taylor S. R. and Jakeš P. (1974) The geochemical evolution of the moon. *Proc. Lunar Sci. Conf. 5th*, p. 1287-1305.
- Taylor S. R., Kaye M., Nance W., Muir P., Rudowski R., and Ware N. (1972) Composition of the lunar uplands: Chemistry of Apollo 14 samples from Fra Mauro. *Proc. Lunar Sci. Conf. 3rd*, p. 1231-1249.
- Usselman T., Lofgren G. E., and Donaldson C. (1975) Experimentally reproduced textures and mineral chemistries of high titanium mare basalts (abstract). In *Lunar Science VI*, p. 835-837. The Lunar Science Institute, Houston.
- Vinogradov A. P. (1971) Preliminary data on lunar ground brought to earth by automatic probe Luna 16. *Proc. Lunar Sci. Conf. 2nd*, p. 1-16.
- Walker D., Longhi J., and Hays J. F. (1972) Experimental petrology and origin of Fra Mauro rocks and soil. *Proc. Lunar Sci. Conf. 3rd*, p. 797-817.
- Wasserburg G. J., Turner G., Tera F., Podosek F. A., Papanastassiou D. A., and Huneke J. C. (1972) Comparison of Rb-Sr, K-Ar and U-Th-Pb ages; lunar chronology and evolution (abstract). In *Lunar Science III*, p. 788-790. The Lunar Science Institute, Houston.
- Weill D. F., McKay G. A., Krindellbaugh S. J., and Grutzeck M. (1974) Modelling the evolution of Sm and Eu abundances during lunar igneous differentiation. *Proc. Lunar Sci. Conf. 5th*, p. 1337-1352.

The Crystallisation Trends of Spinel in Tertiary Basalts from Rhum and Muck and Their Petrogenetic Significance

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Abstract. Spinel is commonly observed in alkali olivine basalts and olivine basalts that form the "Plateau Magma Series" of the British Tertiary Province. The spinels are either partly or wholly enclosed within olivine or may have adhered to olivine surfaces, and have undergone cation exchange and reaction with the cooling basaltic melt. Detailed microprobe traverses indicate complex exchanges involving Fe–Mg, Cr–Al, Fe^{3+} – R^{3+} and Fe^{2+}Ti – R^{3+} substitutions. Some of these changes are due to a reaction with liquid that produced plagioclase and resulted in Al depletion in the spinel. A complex series of solid solutions between hercynite-magnesioferrite-chromite and Al–Cr-titonomagnetite, is indicated in a combination that precludes the disappearance of spinel by a simple peritectic reaction with the melt. The initial spinels are compositionally distinct from the chromites found in the Rhum layered series and underline the great compositional variability of liquidus spinels that can crystallise from basaltic liquid. Some of this variability may relate to the changing solubility of Cr, which behaves as a trace element, in basaltic liquids in response to slight changes in the structure of the melt.

Introduction

Phase relations in the pertinent parts of the systems CaO – MgO – Al_2O_3 – SiO_2 and SiO_2 – MgO – Cr_2O_3 suggest that a spinel phase should crystallise at or near the liquidus in melts of basaltic composition. Basalts and basic layered intrusions commonly contain a few percent of spinel, but the disappearance of this phase as crystallisation proceeds indicates a reaction relationship may operate between spinel and liquid. Peritectic reactions involving spinel may be predicted from phase relations in the above synthetic systems and have been inferred from studies of layered intrusions (Irvine, 1967; Henderson, 1975). However, spinels in layered intrusions frequently show post-cumulus reactions that modify the initial spinel composition (Henderson and Suddaby, 1971; Hen-

* LDGO Contribution no. 2575

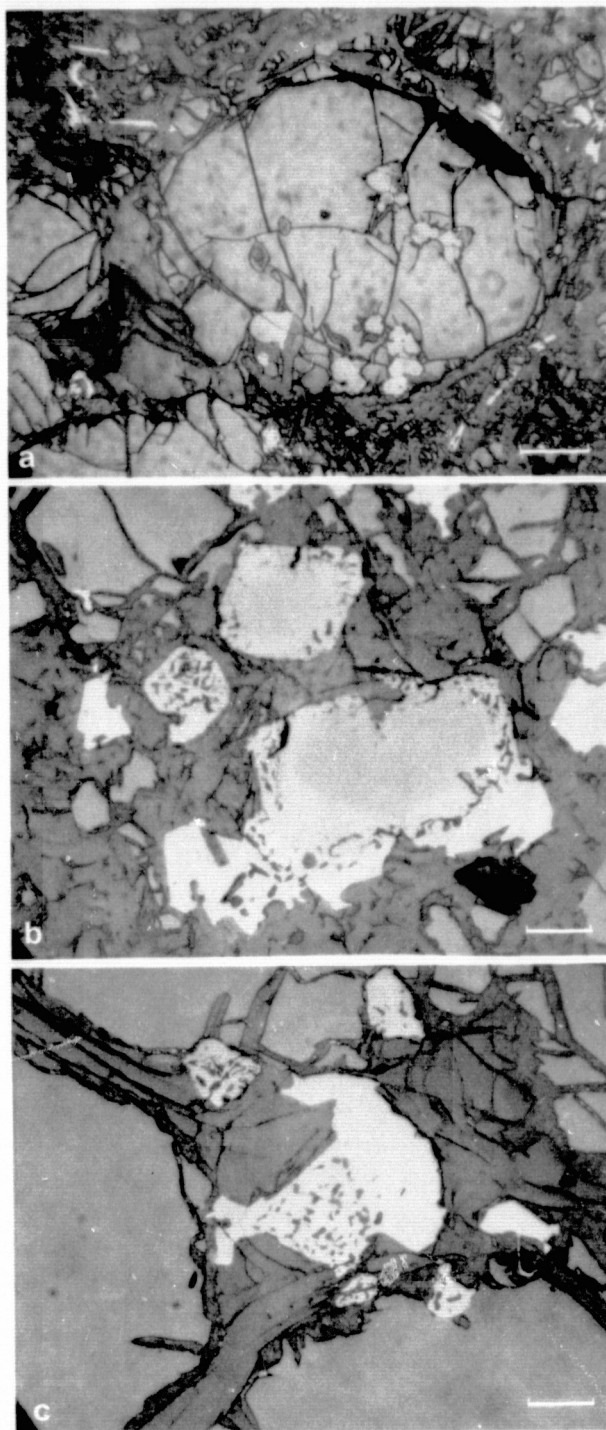


Fig. 1a-c. Textures of spinels in basalt M12

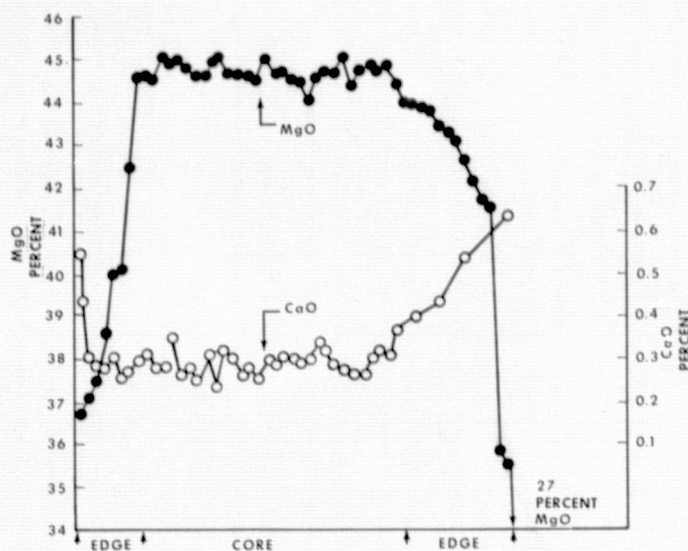
a Fragmented olivine phenocryst wholly and partly enclosing zoned spinels. Note some of the spinels have broken out completely into the matrix. Scale bar is 300 microns

b Zoned spinels partly reacted with basaltic melt. The aluminous spinel in the cores are less reflective and zone outward to Al-Ti chromite. Reaction with the melt to produce plagioclase at the expense of spinel (s.s) is represented by a "wormy" texture. Scale bar is 100 microns

c Extensive reaction between spinel and melt to form a symplectic intergrowth of Al-poor spinel and plagioclase in an embayment within olivine. Similar textures develop within discrete spinels totally removed from olivine, suggesting that olivine is not involved in the reaction. Note the rim of more highly reflective titanomagnetite. Scale bar is 100 microns

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Fig. 2. Traverse across a phenocrystic olivine containing spinel. Note the overall homogeneity with respect to Mg-Ca and strong zoning within a thin marginal zone



derson, 1975) and the large difference in sinking velocity between spinel and ferromagnesian minerals (Jackson, 1971) can lead to ambiguity regarding the crystallisation relationships between intimately associated spinels and silicate phases. Variations in the compositions of spinel within the Rhum layered series have been documented by Henderson and Suddaby (1971), Henderson (1975) and Donaldson (1975) in which two distinct trends were recognised. One trend involved a gradual increase in Al/Cr ratio at relatively constant Fe^{3+} , the other involved an enrichment in Fe^{3+} at the expense of both Al and Cr. However, Donaldson (1975) has observed the opposite trend to the latter. In the present study, spinels occurring in transitional olivine basalts from the Islands of Rhum and Muck in the British Tertiary Province, have been studied in detail with regard to their overall chemical variability and relationship to silicate phases. The chemical variability in the spinels is related to the extent to which they have been exposed to the cooling basalt magma, hence it is possible to document the changes that take place during reaction of spinels with silicate liquid.

A series of cation substitutions takes place involving $\text{Fe}^{2+} - \text{Mg}^{2+}$; $\text{Cr} - \text{Al}$; $\text{Fe}^{3+} - \text{Cr}$, Al ; and Fe , $\text{Ti} - \text{Al}$, Cr , exchanges. These substitutions are more complex and extensive than those observed in spinels from basic layered intrusions, possibly due to the limited proportion of intercumulus liquid in the latter, limited temperature range over which cumulus spinel was in contact with intercumulus liquid, or the major element buffering effect of surrounding cumulus silicate phases.

Petrochemistry of Zoned Spinel in Basalts

Spinel has been analysed in two basalts, an alkali olivine basalt (M12) from Muck and a transitional alkali olivine basalt (SR 157) from Rhum. In both

Table 1. Selected Microprobe analyses of zoned spinels in sample M12

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Al ₂ O ₃	33.39	30.63	28.85	29.00	28.56	25.86	17.25	7.61	28.93	24.78	5.34	4.15	2.33	27.76	28.50	9.28	4.62	1.93
Cr ₂ O ₃	21.58	21.83	21.51	23.03	22.91	22.00	20.23	13.54	20.46	18.89	9.41	3.24	1.20	19.46	25.40	21.03	14.48	1.51
Fe ₂ O ₃	15.51	15.29	16.92	14.74	13.59	13.10	10.14	18.72	17.00	1.36	16.19	12.47	13.19	14.56	11.15	16.66	17.22	13.63
FeO	9.40	15.08	16.25	18.42	21.15	24.84	35.21	37.89	18.86	37.37	42.62	48.74	52.62	24.10	22.80	35.38	40.60	51.85
MnO	0.46	0.61	0.50	0.53	0.56	0.60	0.74	0.75	0.58	0.74	0.75	0.93	2.53	0.60	0.58	0.74	0.79	2.36
MgO	18.36	14.45	13.74	12.22	10.59	9.09	5.94	5.40	11.92	5.77	4.92	4.85	0.68	9.56	9.19	5.25	4.67	1.31
TiO ₂	0.92	1.40	1.74	1.52	1.93	3.92	11.27	15.62	1.63	11.90	20.07	24.71	27.04	3.61	1.48	11.96	17.65	26.75
Total	99.62	99.29	99.51	99.46	99.46	99.29	99.33	100.78	99.53	99.38	100.81	99.31	99.09	99.59	99.65	99.10	100.30	99.34
Al	9.12	8.64	8.16	8.32	8.32	7.68	5.36	2.48	8.32	7.44	1.76	1.28	0.72	8.16	8.32	3.04	1.60	0.64
Cr ₃	3.92	4.16	4.08	4.40	4.48	4.40	4.24	2.96	3.92	3.76	2.08	0.72	0.24	3.84	4.96	4.56	3.28	0.32
Fe ₂	2.64	2.72	3.04	2.72	2.48	2.48	2.00	3.92	3.12	0.24	3.44	2.64	2.96	2.72	2.08	3.44	3.68	3.04
Fe	1.76	3.04	3.28	3.76	4.40	5.20	7.76	8.88	3.84	7.92	10.16	11.92	13.12	5.04	4.72	8.16	5.92	12.80
Mn	0.08	0.08	0.08	0.08	0.08	0.16	0.16	0.16	0.16	0.16	0.16	0.24	0.64	0.16	0.16	0.16	0.16	0.56
Mg	6.32	5.12	4.96	4.40	3.84	3.36	2.32	2.24	4.32	2.16	2.08	2.00	0.32	3.52	3.44	2.16	2.00	0.56
Ti	0.16	0.24	0.32	0.24	0.32	0.72	2.24	3.28	0.32	2.24	4.32	5.36	6.08	0.64	0.24	2.48	3.76	5.92
Total cations	24.00	24.00	23.92	23.92	23.92	24.00	24.08	23.92	24.00	23.92	24.00	24.16	24.08	24.08	23.92	24.00	24.00	24.00
Cr/Cr+Al	0.30	0.32	0.33	0.35	0.35	0.36	0.44	0.54	0.32	0.34	0.54	0.34	0.24	0.32	0.38	0.60	0.67	0.34
Mg/Mg+Fe ²	0.78	0.63	0.60	0.54	0.47	0.39	0.23	0.20	0.53	0.21	0.17	0.14	0.02	0.41	0.41	0.21	0.17	0.04
Fe ³ /Fe ³ +Al+Cr	0.17	0.18	0.20	0.17	0.16	0.17	0.17	0.42	0.20	0.02	0.47	0.57	0.75	0.18	0.13	0.31	0.43	0.75
Ti/Ti+Al+Cr	0.01	0.02	0.03	0.02	0.03	0.06	0.19	0.37	0.02	0.17	0.52	0.73	0.86	0.05	0.02	0.24	0.43	0.85
Fe ³ /Fe ³ +Fe ²	0.60	0.47	0.48	0.42	0.36	0.32	0.20	0.30	0.44		0.25	0.18	0.18	0.35	0.31	0.29	0.28	0.19

Notes to Table 1: M12 is an alkali olivine basalt (2% normative nepheline) from Isle of Muck, Inner Hebrides. Analyses 1–8 represent a traverse across a spinel partly enclosed in olivine (analysis 1) and partly reacted with melt (analysis 8). Analyses 9–13 are a core to rim traverse of a spinel strongly reacted with melt. Analyses 14–18 are partly reacted spinel. Fe₂O₃ values computed assuming stoichiometry, structural formulae on basis of 32 oxygens

Table 2. Selected microprobe analyses of zoned spinels in SR157

	1	2	3	4	5	6	7	8	9
Al ₂ O ₃	46.08	45.91	37.00	32.42	25.88	21.91	14.24	6.56	4.56
Cr ₂ O ₃	8.35	10.11	10.94	12.75	13.53	13.80	12.68	5.53	0.88
Fe ₂ O ₃	16.18	13.60	20.54	21.26	24.38	26.35	31.69	32.01	26.67
FeO	9.36	11.65	12.40	15.92	19.39	22.70	25.86	37.29	44.37
MnO	0.05	0.07	0.09	0.17	0.20	0.21	0.23	0.33	0.48
MgO	20.01	18.61	17.36	15.22	12.92	10.71	8.68	5.28	3.88
TiO ₂	0.83	0.91	1.97	2.66	3.90	4.55	6.34	12.51	18.27
Total	100.86	100.86	100.60	100.40	100.20	100.23	99.72	99.91	99.11
Al	11.68	11.76	9.84	8.96	7.44	6.48	4.48	2.16	1.60
Cr ₃	1.44	1.76	2.00	2.40	2.64	2.72	2.64	1.20	0.24
Fe ₂	2.64	2.24	3.52	3.76	4.48	5.04	6.40	6.80	5.84
Fe	1.68	2.08	2.40	3.12	4.00	4.80	5.76	8.80	10.80
Mn	—	—	—	—	0.08	0.08	0.08	0.08	0.08
Mg	6.40	6.00	5.92	5.28	4.72	4.00	3.44	2.24	1.68
Ti	0.16	0.16	0.32	0.48	0.72	0.88	1.28	2.72	4.00
Total cations	24.00	24.00	24.00	24.00	24.08	24.00	24.08	24.00	24.24
Cr/Cr + Al ₂	0.11	0.13	0.17	0.21	0.26	0.30	0.37	0.36	0.11
Mg/Mg + Fe	0.79	0.74	0.71	0.63	0.54	0.46	0.37	0.20	0.13
Fe ³ /Fe ³ + Al + Cr	0.17	0.14	0.23	0.25	0.31	0.35	0.47	0.67	0.77
Ti/Ti + Al + Cr	0.01	0.01	0.03	0.04	0.07	0.09	0.15	0.45	0.69
Fe ³ /Fe ³ + Fe ²	0.61	0.52	0.59	0.55	0.53	0.52	0.53	0.44	0.35

Notes to Table 2. SR157 is an olivine basalt (3% normative hypersthene) from Rhum, Inner Hebrides. Analyses 1–9 represent a traverse from pristine spinel (analysis 1) enclosed within olivine to reacted spinel (analysis 9) in contact with melt. Fe₂O₃ values and structural formulae computed as in Table 1

samples some spinels are enclosed by olivine which prevented subsequent reaction between spinel and the silicate melt (Figure 1a). Microprobe traverses across olivines enclosing spinel (Figure 2) indicate they are largely unzoned except for thin marginal region where zoning is pronounced. The Fe/Mg ratio of the olivine also remains unaffected by the enclosing spinel. Probably spinel began to crystallise prior to eruption, closely followed by olivine which may have nucleated on the spinels, and grew in an isothermal environment prior to eruption. The zoned margins represent more rapid olivine growth following eruption and cooling. The spinels enclosed within olivine do not appear to have undergone cation exchange with the olivine. However, turbulent flow following eruption resulted in fragmentation of some of the olivines and the spinels were partly exposed to the cooling silicate melt. As a result of these conditions the spinels underwent degrees of reaction and cation exchange with the melt (Figure 1b, c).

Microprobe traverses across selected spinel grains are shown in Tables 1 and 2 and the main cation variations are shown in Figures 3 and 4. The variations in composition represent the spectrum of cationic substitutions

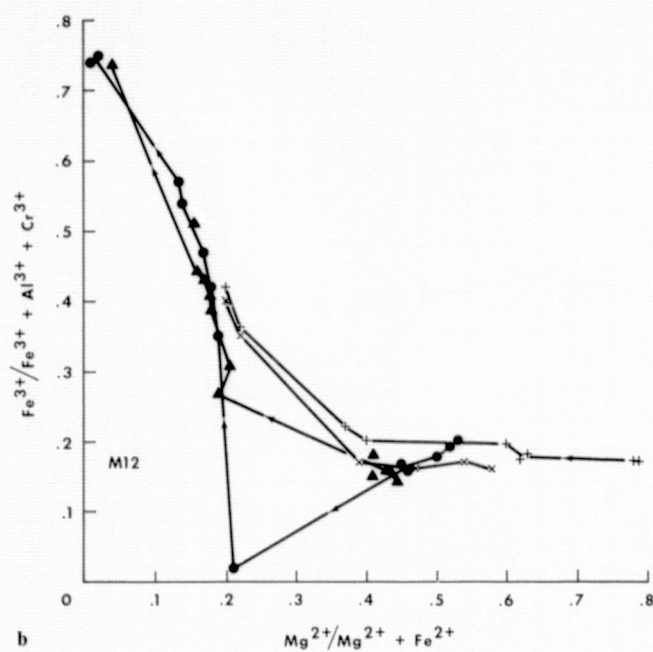
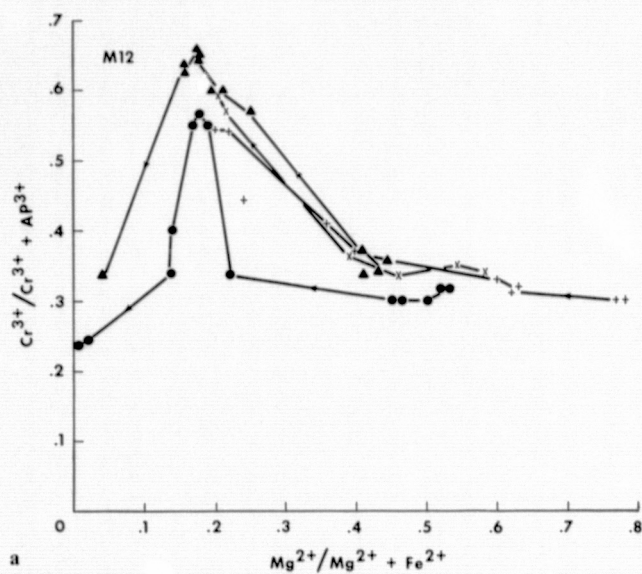
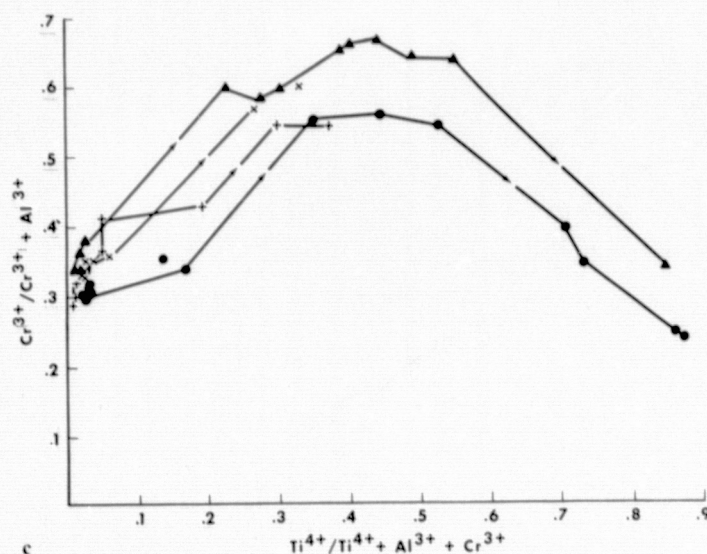


Fig. 3a-c. Cation variations in zoned spinels from alkali olivine basalt M12

a Variations in $Mg/(Mg + Fe^{2+})$ relative to $Cr/(Cr + Al)$. Individual grain traverses are represented by different symbols. Arrows represent directions of core to rim zoning

b Variations in $Mg/(Mg + Fe^{2+})$ relative to $Fe^{3+}/(Fe^{3+} + Cr + Al)$. Symbols as in Figure 3a

c Variations in $Ti/(Ti + Al + Cr)$ relative to $Cr/(Cr + Al)$. Symbols as in Figure 3a



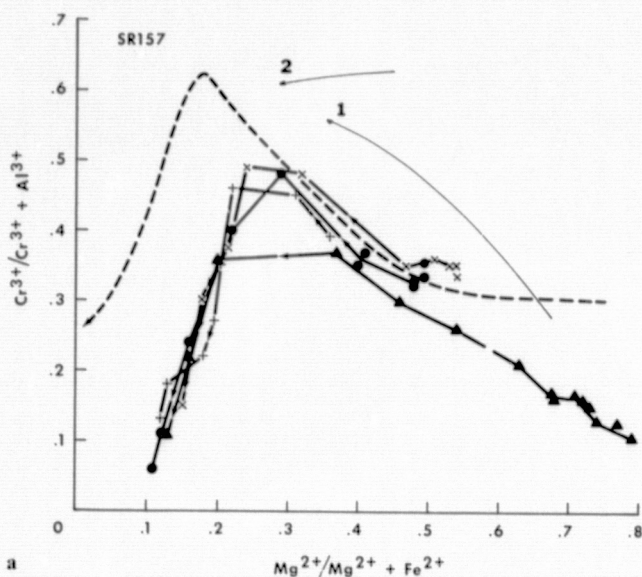
produced by spinels which have reacted with the silicate melt to varying degrees. The original spinels crystallised from the two basalts are not compositionally equivalent. Spinels from the olivine basalt SR157 are noticeably more enriched in Al_2O_3 relative to Cr_2O_3 but have similar Mg/Fe ratios to spinels in the alkali olivine basalt M12 (Figures 2a, 3a).

Reaction with the silicate melt results in a series of cation exchanges. These involve single-cation substitution of Fe^{2+} for Mg^{2+} , Cr^{3+} for Al^{3+} , Fe^{3+} for Cr^{3+} and Al^{3+} . Extensive reaction with the liquid resulted in enrichment in Ti in the spinels probably by a coupled substitution of $\text{Fe}^{2+}\text{Ti}^{4+}$ for $\text{Al}^{3+}\text{Cr}^{3+}$.

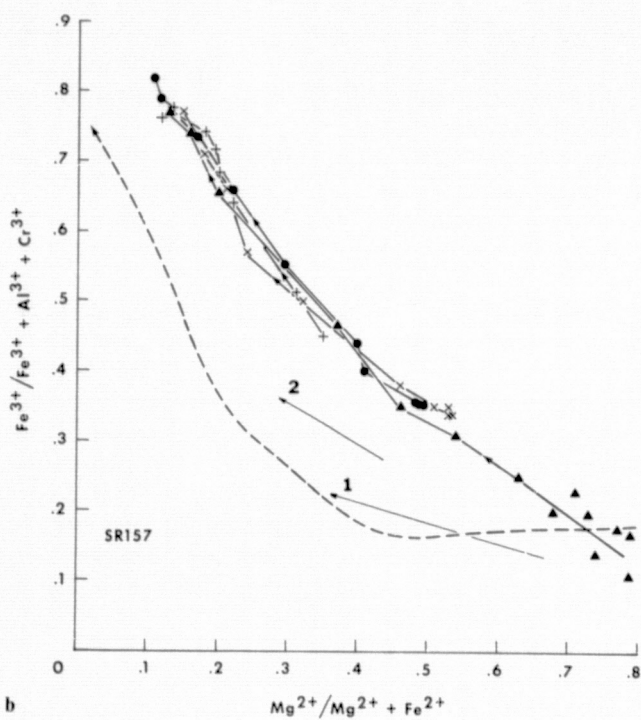
Although the reaction trends are similar for spinels in both basalts, in detail they show some differences. For instance, spinels from the olivine basalt show a continuous increase in the $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Cr} + \text{Al})$ ratio as the Mg/Fe ratio decreases, whereas the former ratio remains either constant or decreases slightly during the initial stages of reaction in the alkali olivine basalt. This difference may be due to initial differences in the $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio in the two melts, since the alkali olivine basalt has a lower $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio (Ridley, 1971). Apart from this initial difference, the subsequent zoning trends are similar, and initially involve a substantial increase in the Cr/Al ratio. This increase coincides with a textural change in which the spinel becomes intergrown with plagioclase in a symplectic texture (Figure 4), reflecting a peritectic reaction:

Aluminous chromite + melt $\rightarrow$ plagioclase + chromite.

These changes are accompanied by gradual increases in the Fe^{3+} and Ti^{4+} content of the spinels, but the $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio remains constant and only decreases markedly once titaniferous magnetite precipitates. Because of the large octahedral site preference energy of Cr^{3+} and none for either Al^{3+} or Fe^{3+} , the increase in ferric ion reflects the substitution of $\text{Fe}^{3+} \rightarrow \text{Al}^{3+}$ rather than



a



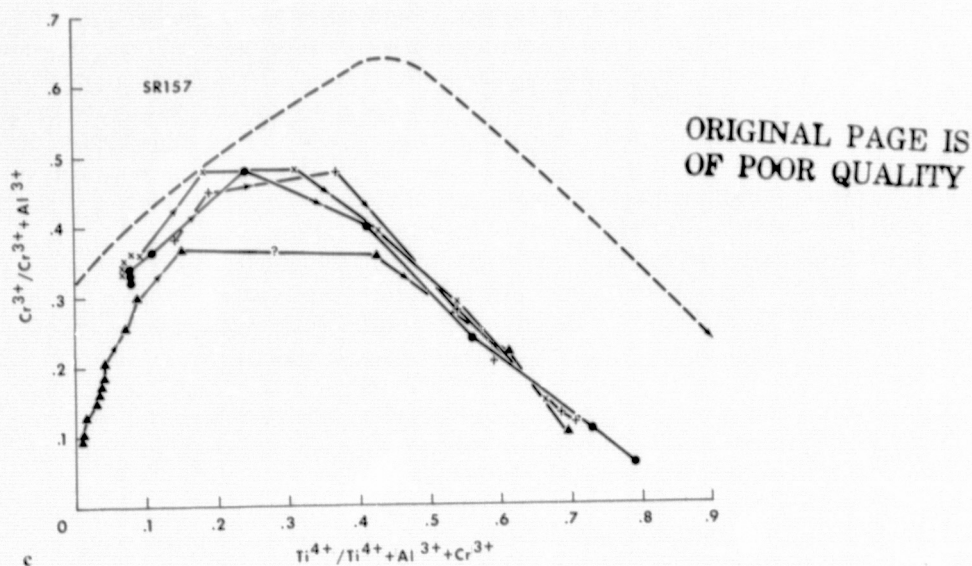
b

Fig. 4a-c. Cation variations in zoned spinels from olivine basalt SR157

a Variations in $Mg/(Mg + Fe^{2+})$ relative to $Cr/(Cr + Al)$. The dashed line is the average trend for zoned spinels in alkali olivine basalt M12. Curves 1, 2 indicate the extent of cation variation in spinels from a spinel seam (curve 1) and discrete spinels with allvalite (curve 2) from the Rhum Layered Series (Henderson, 1975)

b Variations in $Mg/(Mg + Fe^{2+})$ relative to $Fe^{3+}/(Fe^{3+} + Cr + Al)$. Dashed line and curves 1, 2 as in Figure 4a

c Variations in $Ti/(Ti + Al + Cr)$ relative to $Cr/(Cr + Al)$. Dashed line as in Figure 4a



$\text{Fe}^{3+} \rightarrow \text{Cr}^{3+}$ as is evident from the gradually decreasing spinel (s.s) component in Table 2.

The zoned spinels are finally rimmed by titanomagnetite compositionally identical to the discrete grains in the basaltic groundmass. These rims were precipitated directly from the cooling melt upon the surface of previously reacted spinel, essentially protecting the spinels from further cation exchange and reaction with the silicate melt.

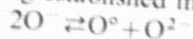
Summarily, the initial spinels to crystallise from these basaltic liquids were Al-chromites differing somewhat in the extent of spinel (s.s)-hercynite solid solution. Exposure to the cooling silicate melt resulted in a complex series of cation exchanges in which the spinel became enriched in the magnesio-ferrite, chromite and ulvospinel (minor) components compared to the original spinel (s.s)-magnesiochromite-hercynite solid solution. The gradual increase in Fe/Mg ratio, enrichment in Ti, but constancy of $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio reflect the changing chemistry of the cooling silicate melt in that the internal, closed-system fraction involves initial Fe-Ti enrichment under relatively constant $f\text{O}_2$ conditions (Ridley, 1973). The spectacular increase in the Cr/Al ratio in the spinels resulted from a peritectic reaction in which the spinel lost Al_2O_3 during the crystallisation of plagioclase.

Crystallisation of Spinels from Basaltic Liquids

These detailed studies indicate that the composition of spinels in equilibrium with basaltic melt changes dramatically in response to decreasing temperature

and oxygen fugacity. The changes involve several cation exchanges but generally suggest that an extensive solid solution series exists between Cr—Al spinels and Fe—Ti spinels, comparable to the chromite-magnetite solution series documented by Hill (1970). These solid solutions preclude the possibility that complex spinels will disappear from a cooling basalt system by a simple peritectic reaction of the type $\text{olivine} + \text{spinel} + \text{liquid} \rightarrow \text{plagioclase} + \text{olivine}$, as would be predicted in simple synthetic systems, and as also suggested by Thayer (1946) and Irvine (1967). Rather the spinel exchanges cations with liquid along a cotectic reaction line that may involve spinel, olivine and plagioclase, resulting in a gradually less aluminous spinel as plagioclase precipitates. Other reactions are possible, depending upon the bulk composition of the system, the composition of the initial spinel and the activities of various cations (Cr, Al, Ti, Fe^{2+} , Fe^{3+}) in the liquid as it fractionates. Total reaction of Cr—Al spinel may only occur once pyroxene crystallises, although as observed here this was precluded by precipitation of ulvospinel-magnetite which effectively shielded the spinels from further reaction with the liquid.

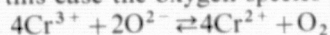
Basaltic liquids are capable of crystallising liquidus spinels of widely varying composition including Al-poor chromites and Cr-rich hercynite-spinel solid solutions. Generally there is a poor correlation between the bulk composition of the basalt and the composition of the liquidus spinel, particularly in Cr/Al ratio. Basalts with only a few hundred ppm Cr will precipitate a Cr-bearing spinel (Hill, 1970) suggesting a limited solubility of Cr in basaltic liquids. In this respect, Cr is an interesting element to study further since, unlike the other major cations in the spinel structure, it acts as a trace element in the silicate liquid. Its crystallochemical behaviour must therefore be affected by the structure of the liquid, and changes in the structure may have important consequences for the solubility of chromite in the melt as well as the precipitation of chromite from the melt. This can be illustrated in two ways, firstly with reference to the observation that the solubility of Cr in basaltic liquids increases with increasing $p\text{O}_2$ (Hill and Roeder, 1974). This is indicated by the precipitation of chromite from basaltic liquids containing more than 400 ppm Cr at $f\text{O}_2$ values less than 10^{-6} – 10^{-7} atm. (Hill and Roeder, 1974). This behaviour can readily be understood by relating changes in oxygen fugacity to changes in liquid structure. The polymerisation of silicate liquids results in an equilibrium being established in terms of oxygen species (Toop and Sammis, 1962).



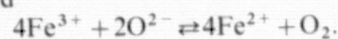
in which O^- are singly bonded oxygen ions, O° are doubly bonded oxygens and O^{2-} are free oxygen ions. A shift of the equilibrium to the left results in a lower degree of polymerisation, and hence more octahedral sites, a shift to the right results in a higher degree of polymerisation and less octahedral sites. Under high oxygen fugacities the melt contains more free oxygen ions, and equilibrium shifts to the left as the melt depolymerises. Cr^{3+} has a high octahedral site preference energy ($37.6 \text{ Kcal mole}^{-1}$, Burns, 1970) and since it is a trace constituent in basaltic melts its solubility will be sensitive to the availability of octahedral sites. Hence depolymerisation with increasing $f\text{O}_2$ should increase the solubility of chromite in the liquid and hence the $f\text{O}_2$ condi-

tions at the site of partial melting will have important consequences for the Cr content of the erupted liquid.

Secondly, during the crystallisation of a spinel phase, other things being constant i.e., the concentration of Cr in the liquid, it is well established that increasing fO_2 will promote the precipitation of spinel from basic magmas. In this case the oxygen-species equilibrium can be written as:



and



In both these cases increasing fO_2 results in increases in Cr^{3+}/Cr^{2+} and Fe^{3+}/Fe^{2+} ratios. However, the redox potentials of these reactions are such that within the range of Fe^{3+}/Fe^{2+} expected for basaltic magma the Cr^{2+} content of the magma will be negligible. Hence the antipathetic relationship between chromite solid solution in the spinel phase and fO_2 must largely be determined by the availability of Fe^{3+} -bearing "components" (magnesioferrite, magnetite) in the melt. The fact that chromite is a substantial component of liquidus spinels, when we consider its dilute concentration in basaltic melts, must be largely due to the availability of abundant octahedral sites once the spinel begins crystallising.

Irvine (1975) has also considered the behaviour of Cr with reference to the structure of silicate melts at the Muscox intrusion, concluding that the occasional precipitation of abundant chromite was the result of periodic contamination of basaltic melt with granitic melt. There are however, many controls on silicate melt structure, one of which has been discussed above; another would be the concentration of dissolved water (Kushiro, 1975). It is emphasized that quite small changes in the availability of octahedral sites in the liquid may have a dramatic effect on the behaviour of transitional series trace elements whilst having little or no effect on cations present in major proportions or elements without octahedral site preference energies. There are probably many other factors, which determine the composition of liquidus spinels in basaltic liquids, especially the initial concentration of Cr in the liquid which itself would be a function of temperature and pressure conditions in the zone of partial melting and the mineralogy of the source material.

It is interesting to note that the liquidus spinels examined in this study are quite distinct from the more chromite-rich spinels found in the Rhum Layered Series (Henderson and Suddaby, 1971; Henderson, 1975; Donaldson, 1975) and yet the basalts are not distinctly different from the proposed parental liquid to the Rhum layered rocks (Brown, 1956)¹. Additionally, well-defined accumulations of spinel are observed in only two units out of about 19 rhythmic units of olivine, plagioclase and clinopyroxene. This suggests extensive crystallisation of spinel in the Rhum magma chamber only took place under *abnormal conditions of crystallisation*, yet these conditions were not reflected in any composition changes in the silicate phases (Wager and Brown, 1967). Thus large-scale contamination of the basaltic magma, of the kind envisaged by Irvine (1975),

¹ However, Donaldson (1975) suggests the parental liquid was closer in composition to a eucrite which conceivably may have been quite rich in Cr_2O_3 .

is precluded². Periodic influx of magma having a slightly lower oxygen partial pressure or lower water content, may be sufficient to promote the precipitation of chromite prior to the appearance of olivine. The residual liquid would hence be strongly depleted in Cr to the extent where crystallisation of chromite was slowed and ceased once clinopyroxene began to crystallise.

The cation exchanges documented here from individual basalt samples are complex and extensive as a result of incomplete reaction and melt fractionation and in general sense are comparable to the changes in spinel composition observed with upward progression in basic layered intrusions. In the latter cases, compositional variations are ascribed to subsolidus re-equilibration and reaction between cumulus minerals and intercumulus liquid. In the Rhum intrusion the pattern of Al enrichment at the expense of Cr (Henderson and Suddaby, 1971) and Cr+Al substitution for Fe^{3+} (Donaldson, 1975) are opposite to those described here, and imply an *increase* in temperature during reaction, as noted by the above authors. Such a situation might arise if the heat from hotter magma convection along the chamber floor conducted downwards through the cumulus material.

The comparatively limited extent of post-cumulus reaction in most cumulus spinel suggests a combination of limited volume of intercumulus liquid, limited contact between spinel and liquid (possibly as a result of filter-pressing loss of liquid), and a closer approach to true equilibrium exchange between the spinel and liquid compared to the reactions described here.

Conclusions

The cores of spinels that spilled into the basaltic liquid have diffuse boundaries and are chemically gradational with the rimming spinel. These features suggest that the chemical zoning has resulted from a reaction between spinel and liquid whereby the spinel was made over to more Fe- and Ti-rich spinel in response to the changing composition of the basaltic liquid. Superimposed upon this was a peritectic-type reaction in which aluminous spinel was made over to chrome-spinel with the precipitation of plagioclase. The changing composition of the spinel in terms of Fe^{2+} , Mg, Ti, Fe^{3+} and Cr must therefore reflect similar changes in the liquid as the major silicate phases olivine, plagioclase and clinopyroxene precipitated and the oxygen fugacity and structure of the liquid changed.

² The Rhum pluton is intimately associated with large volumes of granophyre that probably developed by melting of Precambrian rocks that roofed the magma chamber (Wager and Brown, 1967). Irvine (1975) has noted that this is also common association in many layered intrusions, proposing that basalt-granite mixing may consequently take place. There is clear evidence for basalt-granite hybridisation on Rhum with a dramatic increase in the precipitation of spinel (Dunham, 1964) and minor mixing of basalt with granophyre within the Rhum magma chamber cannot be precluded. Periodic influx of new magma (Wager and Brown, 1967) would provide a suitable mixing mechanism. Hybridisation may also be important in the formation of the enigmatic "mugearites" of Rhum and Canna which have precipitated highly magnesian proxenes (Ridley, 1973).

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References

- Brown, G.M.: The layered ultrabasic rocks of Rhum, Inner Hebrides. *Phil. Trans. Roy. Soc. London, Ser. B* **240**, 1-53 (1956)
- Burns, R.G.: Mineralogical applications of crystal field theory. London: Cambridge University Press 1970
- Donaldson, C.H.: A petrogenetic study of harrisite in the Isle of Rhum pluton, Scotland. Unpubl. Ph. D. thesis, Univ. St. Andrews (1975)
- Dunham, A.C.: A petrographic and geochemical study of back-veining and hybridization at a gabbro-felsite contact in Coire Dubh, Rhum, Inverness-shire. *Mineral. Mag.* **33**, 887-902 (1964)
- Henderson, P.: Reaction trends shown by chrome-spinels of the Rhum layered intrusion. *Geochim. Cosmochim. Acta* **39**, 1035-44 (1975)
- Henderson, P., Suddaby, P.: The nature and origin of the chrome-spinel of the Rhum layered intrusion. *Contrib. Mineral. Petrol.* **33**, 21-31 (1971)
- Hill, R., Roeder, P.: The crystallisation of spinel from basaltic magma as a function of oxygen fugacity. *J. Geol.* (1974)
- Irvine, T.N.: Chromian Spinel as a petrogenetic indicator, Part 2. Petrologic applications. *Can. J. Earth Sci.* **4**, 71-103 (1967)
- Irvine, T.N.: Crystallisation sequences in the Muscox intrusion and other layered intrusions—II. Origin of chromitite layers and similar deposits of other magmatic arcs. *Geochim. Cosmochim. Acta* **39**, 991-1020 (1975)
- Jackson, E.D.: The origin of ultramafic rocks by cumulus processes. *Fortschr. Mineral.* **48**, 128-74 (1971)
- Kushiro, I.: On the nature of silicate melt and its significance in magma genesis: regularities in the shift of the liquidus boundaries involving olivine, pyroxene, and silica minerals. *Am. J. Sci.* **275**, 411-31 (1975)
- Ridley, W.I.: The petrology of volcanic rocks from the Small Isles of Inverness-shire. *Inst. Geol. Sci. London, Report 73/10*, 55 pp. (1973)
- Thayer, T.P.: Preliminary chemical correlation of chromite with the containing rocks. *Econ. Geol.* **41**, 202-217 (1946)
- Wager, L.R., Brown, G.M.: Layered igneous rocks. San Francisco: W.H. Freeman and Co. 1967

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PETROLOGY OF APOLLO 15 BRECCIA 15459; W. Ian Ridley, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York.

15459 is a glass-matrix breccia collected from the rim of Spur Crater. It contains numerous white clasts, presumably derived from Palus Putredinus. The white clasts are of three distinct types; 1. recrystallized anorthositic gabbro with both granulitic and poikiloblastic texture (Type A), bulk analysis of this type is given by Taylor *et al.* (1973). 2. coarse plagioclase and exsolved pigeonite showing minor cataclasis but no metamorphism (Type B). 3. coarse norite with intergranular texture (Type C). A bulk analysis is given in Taylor *et al.* (1973). The rare mare clasts are gabbros showing minor, local shearing. Microprobe data have been collected for the major mineral phases in the clasts, together with glasses in the matrix. *Glasses.* 50 glass fragments in the matrix were analyzed for nine elements. 2% are high-Ti glasses (13% TiO_2), 20% are similar to the local mare basalts, 44% have green glass composition, 33% are low-alkali high-alumina basalt, 1% are gabbroic anorthosite composition. It is interesting to note that the bulk matrix composition of this breccia is equivalent to low-alkali, high-alumina basalt (Taylor *et al.*, 1973), yet the matrix is clearly polymict. *Type A clasts.* Homogeneous discrete grains of coexisting *orthopyroxene*, *pigeonite*, and *augite* are plotted in Figure 1. Generally these pyroxenes have low Al, Ti contents with $\text{Ti/Al} = 1/2 - 1/3$. In addition, *orthopyroxene* oikocrysts include plagioclase and rarely olivine. Similar textures have been described from A-16 and A-17 breccias, but this breccia seems unique in that the *orthopyroxene* oikocrysts cooled slowly enough to exsolve lamellae of *augite* (Figure 1). Distribution of Al, Ti between host and lamellae are shown in Figure 2. Large clasts of *plagioclase* are homogeneous (An 92) with thin sodic rims (An 69). Chadacrysts have uniform An 92 composition. Opaque phases are dominantly *ilmenite* containing 4% MgO with rare Al-Ti chromite, *Olivine* is rare, as small chadacrysts (Fo 70). *Type B clasts.* Contain large *orthopyroxene* grains with coarsely exsolved *augite* (Figure 1). Average composition from broad beam analysis suggests the original pyroxene was pigeonite. Note these pyroxenes are more Fe-rich than in Type A clasts, and fall into the field of A-16 exsolved pyroxenes described by Brown *et al.* (1973). Coexisting plagioclases are slightly zoned, low-Fe types (An 88-92). *Type C clasts.* The initial pyroxene to crystallize was an aluminous *orthopyroxene* (max. 4% Al_2O_3) continuously zoned to ferropigeonite (Figure 3). The latter contain microscopic exsolution lamellae of sub-calcic ferroaugite. Al-Ti relations are shown in Figure 4, illustrating $\text{Ti/Al} > 1/8$ in core *orthopyroxene* but $< 1/2$ in marginal ferropigeonite. *Plagioclase* is weakly zoned from An 86-73. Opaque phases are Ti-Al chromites, Cr-Al ulvöspinel, ilmenite and rare Cr-Zr armalcolite. *Rare clasts.* The earliest pyroxene to crystallize is pigeonite rimmed by sub-calcic augite and augite. Iron enrichment is very limited. Olivine is abundant, weakly zoned from Fo 61-55. Large spinel grains are usually homogeneous Al-Cr ulvöspinel, occasionally rimmed by ilmenite.

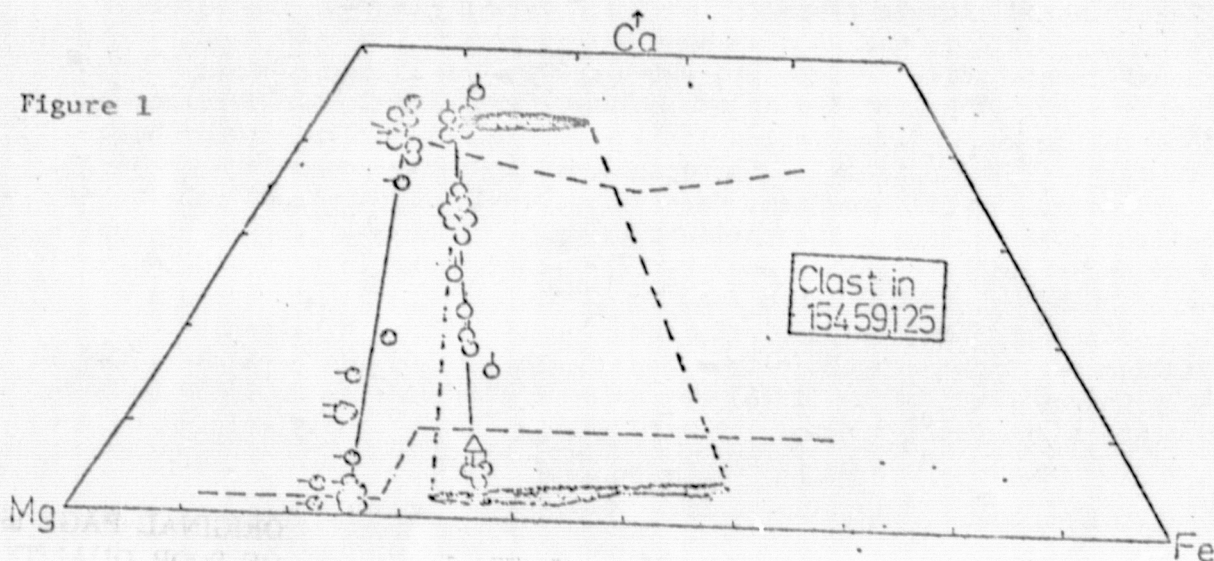
Discussion Another breccia from Spur Crater, 15465 has been described in detail by Cameron and Delano (1973) and appears very similar to 15459 both in matrix texture and clast types. The mare gabbros are probably related to the

BRECCIA 15459

W. Ian Ridley

local mare basalts. The overall pyroxene crystallization trend is similar to that observed for the local basalts, although less iron enriched as a consequence of slower cooling. This would also be compatible with its age of 3.2 AE (Stettler *et al.*, 1973). The presence of these coarse grained rocks indicates slow cooling, so one might expect that some of the variation in Apollo 15 basalts is a consequence of fractional crystallization. Recrystallized anorthositic gabbros (norites of Cameron and Delano ?) seem to dominate the clast population. Their poikiloblastic texture is similar to that observed at other highlands sites, but the presence of exsolved orthopyroxene oikocrysts seems to be unique, and may indicate somewhat slower cooling compared to other poikiloblastic rocks. Coarse grained orthopyroxene and plagioclase clasts probably derived from a plutonic environment, also reflected in coarse exsolution in the pyroxene. The latter compare favorably with exsolved Apollo 16 pyroxenes, so one might conclude that if in both cases the pyroxenes are of local origin, plutonic complexes are of regional extent in the terra regions. (References cited: S.R. Taylor *et al.*, Proc. Fourth Lunar Science Conf., v. 2, p. 1445, 1973; G.M. Brown *et al.*, *Ibid.*, v. 1, p. 505, 1973; K.L. Cameron and J.W. Delano, *Ibid.*, v. 1, p. 461, 1973).
L.D.G.O. Contribution Number - 2199

Figure 1 - Pyroxenes in clasts in 15459,125. Dots are single pyroxene grains and dots with horizontal bar are exsolved oikocrysts, all in Type A. Dots with vertical bar are exsolved inverted pigeonite in Type B. Triangle represents bulk pyroxene composition, shaded areas are A-16 exsolved pyroxenes. **Figure 2** - Ti-Al relationships in 15459,125 clasts. Squares are exsolved oikocrysts, circles are single pyroxene grains, all in Type A. Triangles are exsolved inverted pigeonites in Type B. **Figure 3** - Ti-Al relations in pyroxene from coarse norite clasts. **Figure 4** - Pyroxene crystallization trends in mare gabbro clasts.



BRECCIA 15459

W. Ian Ridley

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Figure 2

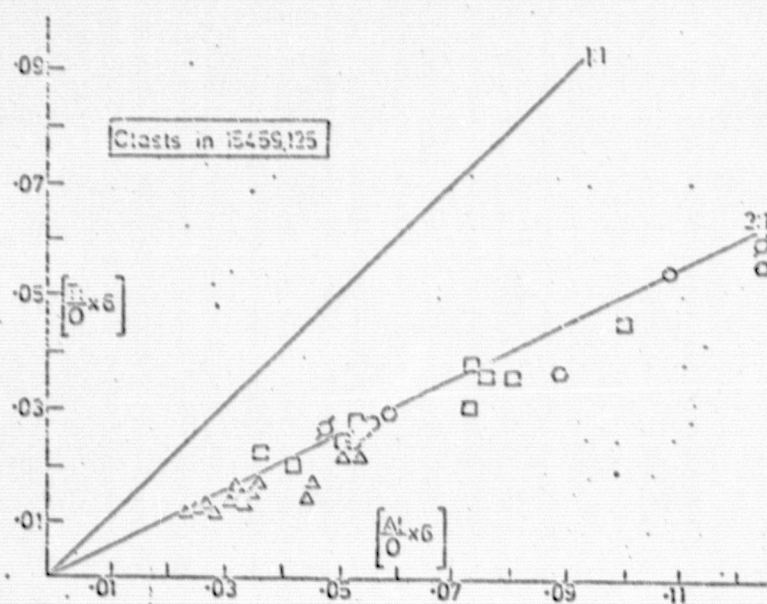


Figure 3

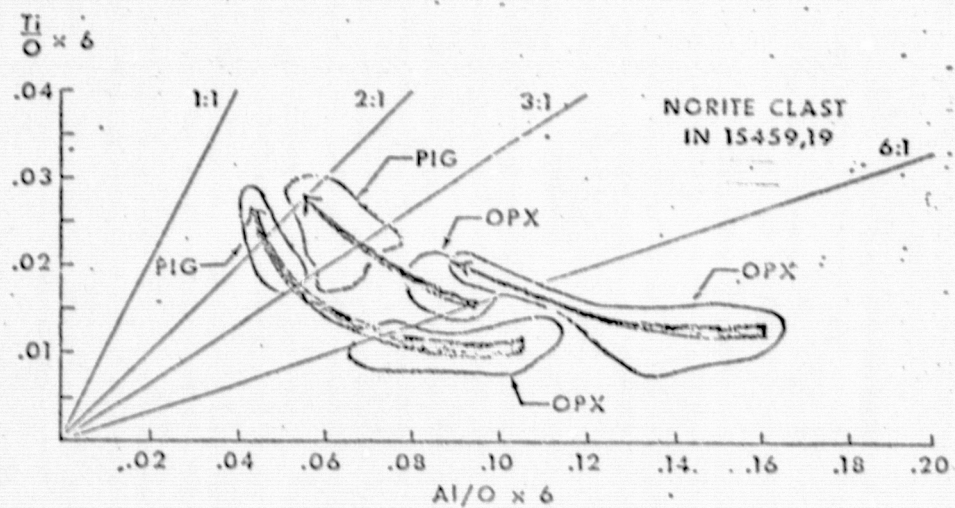
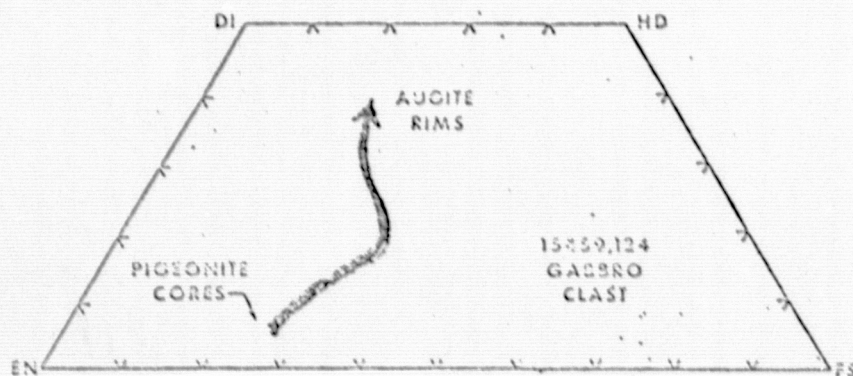


Figure 4



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PETROLOGY OF ALUMINOUS MARE BASALTS IN BRECCIA 14063: W. Ian Ridley, Lamont-Doherty Geological Observatory of Columbia University, Palisades, N.Y.

Mare-like basalts are rarely in the Fra Mauro breccias and poorly described. If they represent fragments of mare basalts comparable in age to those dated from the mare, then the implication is that some Fra Mauro breccias have been reworked, between 3.9 AE and the present. Such reworking may be reflected in a "third-event" postulated from Pb isotope data (Tatsumoto *et al.*, 1972), and ages of some clasts about 3.6 AE. In contrast however, the largest clast, 14053 has an age of 4.0 AE, suggesting that some mare-like clasts may pre-date the final filling of the mare basins. In this event, we have an opportunity to compare these earlier products with the ultimate products of mare volcanism. Both 14053 and 14072 are chemically distinctive from other mare basalts, and may be categorized as aluminous mare basalts (Reid and Jakes, 1974). They are intermediate in composition between the low-Ti mare basalts (A-12, A-15) and high-alumina basalts that may have been abundant in the lunar terra regions. Clearly they may be of petrogenetic significance in bridging the gap between mare and terra volcanism.

Mare-like clasts have been observed in breccia 14063, one of the white rocks considered to have been ejected from the deepest stratigraphic level at Cone Crater. They have a texture defined by a lathy to aciculate plagioclase, lathy ilmenite and intergranular pyroxene. They show no evidence of shock, thermal metamorphism or cataclasis. The somewhat equivocal texture suggests roughly synchronous crystallization of plagioclase and ilmenite, followed by pyroxene. One sample contained brown mesostasis glass flecked with metal dust. Broad beam analyses of these clasts (Table 1) indicates their unique major element chemistry, quite distinctive from other mare basalts. By comparison with the latter, they have higher Al_2O_3 , Na_2O , Mg/Fe ratio; compared to aluminous mare basalts (Reid and Jakes, 1974) they have higher TiO_2 and Mg/Fe ratios. It might be argued that these analyses are non-representative, and although this is plausible, the phase chemistry strongly supports crystallization from a Ti, Al and Mg-rich melt. *Pyroxene.* The earliest crystallized pyroxene is sub-calcic augite, followed by augite and ferroaugite (Table 1, Figure 1). Their enrichment in Ti, Al, Cr is similar to pyroxene crystallized from other high-Ti mare basalts (A-11, A-17). In detail, they differ from these mare basalts in having $Ti/Al > 1/2$ from an early stage in their crystallization history (Figure 1), suggesting the presence of trivalent Ti and by inference, early, highly reducing conditions of crystallization. *Plagioclase.* Shows limited compositional variation (An 31-73). Plagioclase is more sodic than observed in other mare basalts indicating a more alkalic melt, consistent with the major element analysis. Compared to other mare basalts of similar An content they have high contents of MgO and consequently low FeO/FeO + MgO ratios (46-62). If this ratio reflects qualitatively the composition of the liquids from which the plagioclase crystallized, then these melts had higher Mg/Fe ratios than other mare basalts. This is also consistent with the major element analyses. Ion microprobe analyses for Li, Ti, Mg, Sr, Ba shows the plagioclases contain high TiO_2 (.05 - .28 wt.%) and 30-70 ppm Li. Li values are 2-3 times higher than those observed in KREEP plagioclases (Meyer *et al.*, 1974), although it seems

ALUMINOUS MARE BASALTS

W. Ian Ridley

unlikely that they reflect magmas with very high Li contents. Since Mg, Li form a diadochic pair, it seems more likely that the high Mg contents in plagioclases facilitates entry of Li into the plagioclase structure. Caution should then be applied in evaluating distribution coefficients for Li between plagioclase and coexisting silicate liquid. *Ilmenite*. This was the only oxide phase to crystallize, and belongs to the ilmenite-geikielite solid solution series. Maximum MgO value is 7.2% in larger crystals (Table 1) whereas smaller crystals have about 5.6% MgO. They are thus distinct from ilmenites in low-Ti mare basalts, and most comparable to ilmenites in high-Ti mare basalts. The high MgO, TiO₂ are consistent with formation of ilmenite by breakdown of original armalcolite (Haggerty, 1973).

Discussion Aluminous mare basalts are a minor, but potentially important component of the returned samples (Reid and Jakes, 1974). Aspects of the orbital XRF data may also be explained if they were an important part of the mare stratigraphy (N.J. Hubbard, pers. comm.). Aluminous mare basalts may show closest chemical affinities to the low-Ti basalts, such as those cited by Reid and Jakes, whereas those described here have closer affinities to the high-Ti basalts. Also notable is the high Mg/Fe ratio, lower FeO and high Na₂O that gives them a distinctly terrestrial appearance, other than the high TiO₂ content. Their age is unknown but they appear in an aluminous breccia that Schonfeld and Meyer (1973) consider to be pristine Imbrium ejecta. One might summarize that they are then older than other mare samples. If they represent deeply buried mare flows then their observed numerical insignificance may misrepresent their importance in mare stratigraphy. Although one should be cautious here, a similar caution should also apply in overestimating the importance of the high-Fe mare basalts which may simply form a thin veneer to the mare fill.

(References cited: S.E. Haggerty, Proc. Fourth Lunar Science Conf., v. 1, p. 777, 1973; M. Tatsumoto *et al.*, Proc. Third Lunar Science Conf., v. 2, p. 1531, 1972; C. Meyer *et al.*, Proc. Fifth Lunar Science Conf., v. 1, 1974; A.M. Reid and P. Jakes, Lunar Science V, p. 627, 1974; J.V. Smith, Proc. Second Lunar Science Conf., v. 1, p. 143, 1971; E. Schonfeld and C. Meyer, Proc. Fourth Lunar Science Conf., v. 1, p. 125, 1973).
L.D.G.O. Contribution Number - 2193

Figure 1 Ti-Al relationships in clinopyroxenes. Arrows mark trends in individual crystals. Apollo 11 trend shown following Al/Ti = 2 line. Trend of Ca, Fe, Mg variation shown inset.

Figure 2 Fe-Mg variations in plagioclase, compared to Apollo 11 plagioclases of similar An content (After Smith, 1971).

ALUMINOUS MARE BASALTS

W. Ian Ridley

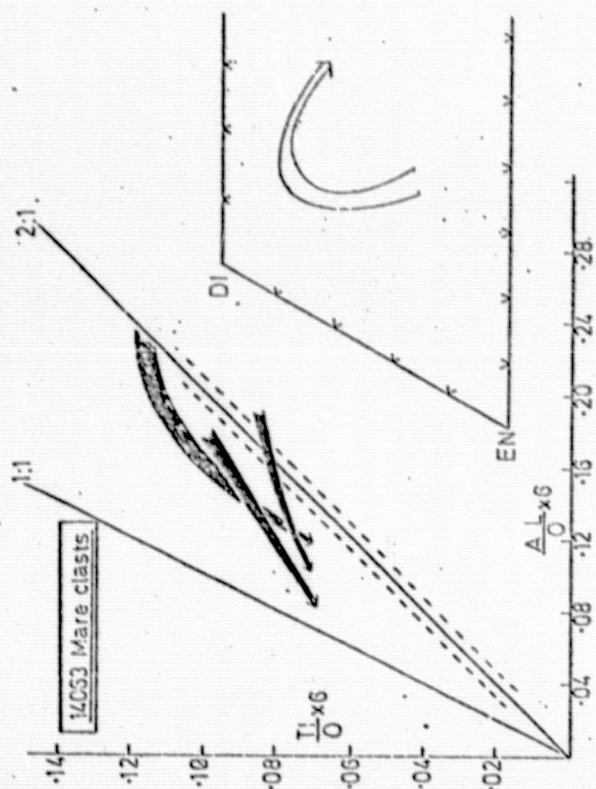
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Figure 1

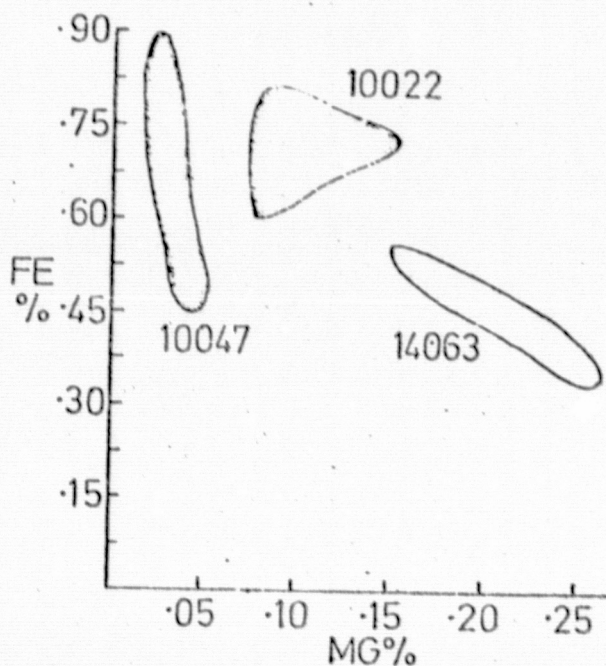


Figure 2

Table 1
Analyses of Components of Mare Clasts in 14063

	1	2	3	4	5	6	7
SiO ₂	45.9	49.69	48.44	47.93	48.99	-	-
TiO ₂	7.3	2.99	2.36	0.03	0.99	56.18	54.44
Al ₂ O ₃	14.4	3.39	1.99	33.13	32.29	0.08	0.13
Cr ₂ O ₃	0.2	0.44	0.16	-	-	0.56	7.59
FeO	10.7	16.99	23.14	0.33	0.53	35.47	38.24
MnO	-	0.22	0.21	-	-	0.34	0.33
MgO	6.7	17.55	8.70	0.38	0.33	7.17	5.64
CaO	11.3	9.51	14.83	16.66	14.38	-	-
Na ₂ O	1.0	-	0.02	1.79	2.59	-	-
K ₂ O	0.1	-	-	0.18	0.32	-	-
Total	97.6	100.78	99.85	100.45	99.93	99.80	99.42

1 Average broad beam analysis of mare clasts

2,3 Subcalcic augite and ferro-augite, respectively

4,5 Core and rim of plagioclase, respectively

6,7 Large, anhedral ilmenite and acicular ilmenite respectively

PETROLOGIC STUDIES OF POIKILOBLASTIC TEXTURED ROCKS; W. Ian Ridley, Mary-Linda Adams, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964

Several detailed petrologic studies have been reported on Apollo 16 and 17 poikiloblastic-textured samples(1,2). In most of these samples the oikocrysts are only weakly zoned, are either orthopyroxene or pigeonite, and may be rimmed by augite. Ridley⁽¹³⁾ has reported on poikiloblastic clasts in breccia 15459 which have inverted pigeonite oikocrysts showing macroscopic augite lamellae. These clasts are fine-grained and must have cooled quite quickly. It appears that coarsely exsolved lunar pyroxenes can be impact produced and are not necessarily indicative of plutonic conditions of formation.

Chadacrysts may be one or more of plagioclase, orthopyroxene, pigeonite, augite and olivine. Presumably the number of chadacryst phases is indicative of either maximum temperature attained during formation of the poikiloblastic rocks or of the mineral complexity of the rock prior to becoming poikiloblastic. For instance the presence of five chadacryst phases in 15459 clasts could indicate a lower formation temperature than most Apollo 16, 17 poikiloblastites, which have only one or two chadacryst phases. Additionally some poikiloblastic samples have interstitial diabasic patches, generally interpreted to reflect previously molten areas. The overall poikiloblastic texture may develop during impact-induced thermal metamorphism involving solid state recrystallisation and diffusion and partial melting. This seems to be the most likely process for formation of most fine-grained poikiloblastic rocks. Alternately, coarsely developed poikiloblastites, e.g., 77017, could result from igneous processes involving intercumulus growth.

Thermal regimes for poikiloblastites can be crudely estimated by consideration of minimum temperatures for mineral equilibration (T_e) using, for instance, the pyroxene geothermometer of Wood and Banno⁽⁴⁾ or the olivine-clinopyroxene geothermometer of Powell and Powell⁽⁵⁾. McCallum *et al.*⁽⁶⁾ have used coexisting orthopyroxene and augite to estimate minimum equilibration temperatures for 77017 of 1050-1100°C; coexisting olivine and augite in this rock are estimated at $T_e=993^\circ\text{C}$. T_e can also be estimated for other poikiloblastites where sufficient phase chemistry data are available. Diabasic areas in 60315,63 give temperatures of 1102°C and 1072°C for coexisting orthopyroxene-augite and olivine-augite, respectively. In contrast coexisting olivine and augite chadacrysts, if assumed to have equilibrated, give lower temperatures of 1001°C. Studies of poikiloblastite 67955 give minimum temperatures of 1007°C for coexisting olivine-chadacrysts surrounded by oikocrystic augite, whereas coexisting orthopyroxene and augite in different clasts (which nonetheless may have equilibrated at the temperatures of breccia formation) give $T_e=1093^\circ\text{C}$. Intergranular, coexisting olivine and augite in 61156,31 give $T_e=1010^\circ\text{C}$. Data for poikiloblastites in 15459,125 allow estimates of minimum temperature for equilibration of orthopyroxene oikocrysts and their augite lamellae (1060°C), chadacrysts of orthopyroxene and augite (1099°C), and chadacrysts of olivine and augite (975°C). For comparison we can calculate T_e values for some other terra samples that have crystallised from melts. Coexisting olivine and augite in 63415 give

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POIKILOBLASTIC TEXTURED ROCKS

W. Ian Ridley

Te=998°C. A plutonic norite clast in 15459,125 with very coarsely exsolved inverted pigeonite gave Te=984°C for final equilibration of pyroxene host and lamellae.

Overall these data indicate minimum temperatures of formation of poikiloblastites of 1000-1100°C. Coexisting olivine-augite give somewhat lower temperatures than orthopyroxene-augite, suggesting diffusion is effective to lower temperatures for the former mineral pair. Although more data need to be integrated, it appears that diabasic areas give higher values for Te than poikiloblastic areas, possibly indicating local patches of melt formed in these rocks. Additionally most of the poikiloblastites are fine-grained and probably cooled quickly relative to plutonic rocks so that Te values may not be significantly lower than formation temperatures for these rocks. Poikiloblastic rocks have a variety of bulk compositions. Some are approximately high-alumina basalts, whereas others are more plagioclase rich and compositionally similar to anorthositic norites. Solidus temperatures for these samples at 1 atm. must be 1050-1070°C, similar to the Te values observed here. If these are also close to formation temperatures, then it is implied that only minute amounts of liquid formed near the solidus and that most poikiloblastites developed in a metamorphic environment.

The geographic spectrum of poikiloblastites can be extended by addition of data for poikiloblastic-textured clasts in Apollo 14 breccias. These are relatively common in the white, anorthositic breccias collected from Cone Crater, but are somewhat rarer in the KREEP breccias. Although initially recognised by LSPET and subsequently described by Wilshire and Jackson(7), no chemical data have as yet been reported. Clasts in the anorthositic breccias 14066,36; 14066,51; 14066,49; 14063,52 have either oikocrysts of orthopyroxene or pigeonite, rarely with rims of augite. Lathy plagioclase is the only chadacryst phase, but relics of large, irregular plagioclase have also been observed. In contrast, poikiloblastic clasts in KREEP breccia 14305,105 and coarse fines 14151,8 appear only to have oikocrysts of weakly zoned augite and chadacrysts of plagioclase. Several of these clasts have irregularly fractured relics of augite. Poikiloblastites in the anorthositic breccias appear to have developed by recrystallisation of plagioclase-rich noritic breccias, whereas those in KREEP basalts may have had more pyroxene-rich precursors. Presumably differences in bulk composition account for the dominance of low-calcium oikocrysts in the one group and calcic oikocrysts in the other. Of the two groups, those found associated with the anorthositic breccias are similar to poikiloblastites described from Cayley-Descartes and Taurus-Littrow regions. Those associated with KREEP breccias may be restricted to the Fra Mauro region.

- References 1. Bence, A.E., Papike, J.J. and Delano, J.W. 1973, *Proc. Lunar Sci. Conf.* 4th, p. 599-611. 2. Simonds, C.H., Warner, J.L. and Phinney, W.C. 1973. *Ibid.* p. 613-32. 3. Ridley, W.I. *Lunar Science VI*. 4. Wood, B.J. and Banno, S. 1973. *Contrib. Mineral. Petro.* 42, p. 109-24. 5. Powell, M. and Powell, R. 1974. *Ibid.*, 48, p. 249-63. 6. McCallum, I.S., Mathez, A.E., Okamura, F.P. and Ghose, S. 1974. *Proc. Lunar Sci. Conf.* 5th p. 287-302. 7. Wilshire, H.G. and Jackson, E.D. 1972. *U.S. Geol. Survey Prof. Paper* 755, 26p.

PREFACE

The Aleutian Islands and the Cayman Trench bear no obvious geologic similarities, yet in many ways they are comparable. This thesis is not an attempt to directly relate these two regions, rather the detailed petrologic and geochemical investigations provide further evidence that the petrochemical nature and evolution of each area are related to the regional tectonics at plate margins.

Unalaska Island, the Cayman Ridge and Nicaraguan Plateau are the results of island arc volcanism caused by plate convergence and subsequent subduction of lithosphere into deep-sea trenches. Volcanic and tectonic activity in the Aleutians is related to the consumption of the Kula Plate, Kula Ridge and Pacific Plate beneath the present arc. In the Cayman Trench, a change from island arc volcanism to oceanic ridge-type volcanism is related to a change in relative movement between the North American and Caribbean Plates. The petrochemistry of igneous rocks from both regions is directly related to the tectonic processes at these active plate margins.

Abstract

The Captains Bay pluton is one of three well-exposed plutons that intrude slightly deformed and metamorphosed Tertiary volcanic and clastic rocks on Unalaska Island in the Aleutian Islands. The pluton is crudely zoned from a narrow gabbroic rim to a heterogeneous central region of granodiorite intruded by numerous aplite dikes.

Major, trace and rare earth element (REE) data elucidate the similarities between the Captains Bay plutonic series and the Aleutian calc-alkaline volcanic series. Systematic variations in major and trace element abundances and increased REE fractionation are consistent with a model of inward fractional crystallization of a parental andesite or high-alumina basalt at shallow (<20 km) depths. Differentiation is initially controlled by the early removal of plagioclase, lesser pyroxene and possibly olivine. With increasing water fugacity ($P_{H_2O} > .5P_T$) amphibole fractionation becomes increasingly important. Border zone gabbros, which represent early crystal cumulates, must be more prevalent at depth to account for the observed volume of intermediate plutonics generated by crystal fractionation. Aplites do not represent residual granitic fluids that were in equilibrium with the plutonic magma. They have chemical affinities with Aleutian rhyolitic ashes but their origin is enigmatic.

Calculated equilibrium temperatures for coexisting pyroxenes indicate that crystallization temperatures were

approximately 950°C and may have been as high as 1210°C. Compositions of coexisting Mn-rich ilmenite and magnetite, ilmenite lamellae in magnetite, and the appearance of hematite, sphene and rutile in more evolved samples suggest a late-stage oxidizing trend in the pluton. Limited chemical variations in ferromagnesian phases and common inverse chemical zoning also imply increasing oxygen fugacity during crystallization of the intrusion.

Low $\delta O^{18}_{(SMOW)}$ values (2.7 to -4.1) of most intermediate plutonic rocks and metamorphosed country rocks indicate that large scale interaction with meteoric groundwater occurred and was probably enhanced by a convective, hydrothermal cell generated by the intrusion. Comparatively low but variable Sr^{87}/Sr^{86} ratios (.70316-.70394) reflect inherent inhomogeneities in the mantle and/or minor effects of contamination as the pluton rose toward the surface.

A multistage petrogenetic model is presented which can explain the observed abundances of Ba, Sr, Rb, K and REE in postulated primary magmas. In this model, depleted mantle above the Benioff Zone is hydrated and contaminated by liquids derived by partially melting (5-10%) subducted oceanic crust (eclogite) containing a small (5%) sedimentary component. Primary magmas are generated by partially melting (10-20%) this garnet-free, modified mantle at depths less than 100 km. Subsequent low-pressure fractionation produces the observed chemical variations in the Captains Bay pluton.

APPENDIX C

Trace element abundancesPlutonic rocks, Captains Bay Pluton, Unalaska Island

	Ti	Zr	Sr	Rb	Y
14	3830	184	492	37	21
16	3580	174	531	33	27
19	4425	150	450	39	24
22	4600	140	474	34	22
25B	3830	164	412	31	24
66C	6300	20.5	698	5	4
70	1310	129	318	76	19
86	3540	161	393	49	20
88	3910	157	525	33	18
88A	4160	167	459	15	18
92	3540	140	428	34	16
170	4100	154	417	28	29
170II	3800	109	418	28	24
173	3350	133	390	40	18
174A	7040	168	403	34	18
174B-AP	610	129	0	160	5
174B-GR	2860	185	407	31	20
176A	-	186	440	35	22
176B	3190	175	416	32	22
177	4640	263	360	43	26
177II	3570	-	402	28	24
177A	3330	-	463	31	9
179	-	-	465	32	22
181II	3350	-	427	29	24
181DK	3220	175	389	38	16
181LT	4830	235	234	79	26
181ADK	3720	205	382	45	18
181B	580	107	-	122	27
181B-GR	2990	169	436	32	26
181BKSP	840	107	0	122	27

APP. C (cont'd.)

	Ti	Zr	Sr	Rb	Y
182	3170	-	460	18	24
183	-	-	425	37	15
183A	-	-	386	28	22
184	-	-	428	34	15
184B	-	-	440	20	20
185	-	-	383	34	20
186	-	-	392	28	20
187A	-	-	388	28	22
187B	-	-	429	29	22
189B	4490	145	365	-	-
189C	5000	190	403	45	26
189D	5430	242	368	49	21
189DII	-	154	402	46	23
189F	4100	219	389	62	23
189FII	-	-	424	50	20
189G	-	-	514	33	13
190	-	-	497	27	15
191	-	-	419	46	16
192	-	-	487	18	23
195A	-	-	734	5	8
195	4490	45	744	3	12
197Pyr	10310	86	147	5	30
197	3490	578	540	1	10
197II	264	130	264	70	9
202	5760	120	547	30	19
202II	4820	82.2	550	-	-
205	5150	22	677	3	8
211	2490	215	282	67	25
212	-	161	446	-	-
213	3510	164	423	-	-
215	-	175	461	35	18
216	-	-	452	40	21
223	-	24	579	5	16
229	-	189	423	-	-

APP. C (cont'd.)

	Ti	Zr	Sr	Rb	Y
232A	-	158	426	-	-
232B-G	3270	155	401	52	24
232B-S	-	189	391	51	24
233X	4260	90.6	604	13	11
234	3140	147	466	-	-
235	1600	142	447	-	-
236	4360	209	405	44	19
237	1660	170	313	63	17
238	5380	142	510	28	16
239	3830	165	458	43	19
239II	-	-	460	37	19
240	3620	205	324	41	21
241	4590	-	426	42	13
245	4690	227	452	67	27
U5 20	3650	200	457	53	21
U5 31	4700	174	446	42	22
U5 49	-	-	482	3.9	23
U5 60	-	-	437	40	21
U5 60A-G	-	-	324	53	14
U5 76A	-	-	460	36	21
U5 85	5210	-	537	25	20
U5 93C-D	-	-	523	31	17
U5 93C-L	-	-	489	8.6	20
U5 96	9075	35	544	7.9	13
U5 97A	8530	-	529	33	24
U5 98	-	-	502	9.4	17
U5 107	-	-	461	28	20
U5 112	-	-	347	62	22
U5 144	3140	-	392	57	21
U5 154C	-	-	317	59	13
U5 157	-	-	439	5.7	17
UN 2	4080	-	397	44	24
UN 4	3060	-	407	68	16

APP. C (cont'd.)

	Ti	Zr	Sr	Rb	Y
UN 5	5220	-	387	34	21
UN 6	5220	-	451	39	23
UN 3A	3660	-	401	63	31
UN 7	4920	-	454	56	21
UN 8	5400	-	384	66	29
UN 10	5400	-	420	47	22
UN 11	5580	-	435	33	23
UN 12	5580	-	454	34	21
UN 29	5220	-	478	54	30
UN 30	6060	-	430	45	26
UN 31	4360	-	-	49	-
UN 32	5160	-	365	62	29
UN 34	5820	-	473	58	23
UN 35	5040	-	358	61	28
UN 37	5940	-	345	29	25
UN 38	6480	-	476	14	15

Volcanic rocks, Unalaska Island

2	3720	139	474	20	21
8	7040	255	736	29	18
8II	8400	243	720	23	20
9	7660	256	614	20	25
26	8170	246	528	14	23
30D	8890	202	461	20	22
40A	5220	277	266	60	38
72B	3540	133	471	15	13
100A	3160	208	420	40	24
104D	5560	201	292	73	20
108A	3250	150	638	12	26
108B	3830	120	527	20	20
108F	2970	102	649	6	13
119	4420	177	345	20	25
128	4020	126	391	20	24

APP. C (cont'd.)

	Ti	Zr	Sr	Rb	Y
131	6090	95	464	15	24
133D	5030	75	379	8.0	15
152	3940	126	446	2	20
155D	7870	119	452	12	20
158	4710	106	501	0	20.
161A	2500	281	227	54	33
165A	2760	129	490	15	13
168G	4380	62.4	312	6.0	22
192	-	-	487	18	23
196	-	-	512	17	19
198X	5630	77	380	14	17
204	6230	135	399	14	22
UN 3B	-	-	478	29	20
U5 51	-	-	509	13.9	19
U5 60A-X	-	-	413	36.5	21
U5 74H	-	107	-	2.0	11
U5 119C	-	-	531	6.1	20
U5 120	4490	-	536	8.0	23
U5 123	-	-	596	27	19
U5 133	-	174	580	7.0	23
U5 142	2520	-	543	43	8
U5 144D	-	-	458	7.3	-
U5 144D2	-	-	462	6.1	23
U5 145	-	-	742	67	3
U5 154D	-	-	430	13	12
U5 174	-	-	543	23	8
MK 2	4600	108	502	27	13
MK 3	3670	150	464	21	16
MK 3A	3960	173	478	26	17
MK 7	4210	43	456	8	11
MK 15	4390	53	504	11	16

APP. C (cont'd.)

	Ti	Zr	Sr	Rb	Y
<u>Sedimentary rocks, Unalaska Island</u>					
162	5345	150.7	544	31	27
162A	3160	113.1	642	62	22
163B	4120	167.7	257	11	29
163E	4420	148.2	253	17	33
166F	5940	140.4	95	125	19

APPENDIX D

Chemical analyses of plagioclase and potassium feldspar in rocks from Unalaska Island

32B AP

	1K	2GM	2K	3GM	3GM	3KR	4K	5K	6GM	6GM	7GM	7GM	7GM	7AGM	8GM
SiO ₂	63.31	63.70	63.84	66.11	65.09	62.80	62.75	63.40	64.55	60.52	62.59	63.59	62.93	63.03	63.09
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	19.54	20.20	19.26	21.76	21.20	20.09	19.53	18.69	21.25	21.45	23.71	22.68	23.04	23.13	23.65
FeO	0.23	0.09	0.03	0.00	0.00	0.64	0.29	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.39
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.10	0.66	0.04	0.49	0.46	0.04	0.04	0.05	1.18	1.07	2.91	2.69	3.24	2.94	3.41
Na ₂ O	2.09	5.49	2.18	11.20	10.87	1.34	2.20	1.56	11.09	10.94	9.36	10.37	9.74	9.82	9.68
K ₂ O	14.31	7.21	14.56	0.26	0.23	15.37	14.65	14.02	0.05	0.06	0.01	0.03	0.07	0.04	0.57
P ₂ O ₅	0.00	0.00	0.00	0.01	0.03	0.04	0.00	0.00	0.01	0.01	0.00	0.03	0.00	0.01	0.03
Total	99.57	97.35	100.18	99.83	97.88	100.33	99.47	97.91	98.13	94.05	98.57	99.38	99.01	98.97	100.82
Si	2.934	2.931	2.942	2.901	2.912	2.904	2.921	2.974	2.889	2.834	2.792	2.822	2.803	2.806	2.777
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.066	1.095	1.045	1.125	1.117	1.095	1.070	1.032	1.120	1.184	1.246	1.185	1.208	1.213	1.227
Fe	0.008	0.002	0.012	0.000	0.000	0.024	0.011	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.014
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.004	0.032	0.001	0.021	0.021	0.001	0.001	0.001	0.056	0.053	0.139	0.127	0.154	0.140	0.160
Na	0.188	0.488	0.193	0.953	0.942	0.119	0.198	0.142	0.961	0.992	0.809	0.892	0.840	0.846	0.825
K	0.846	0.422	0.856	0.014	0.013	0.906	0.870	0.838	0.002	0.002	0.000	0.001	0.002	0.001	0.031
P	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	5.044	4.971	5.049	5.014	5.004	5.050	5.070	4.994	5.028	5.066	4.985	5.027	5.007	5.006	5.034
Al + Si	4.000	4.025	3.987	4.026	4.029	3.999	3.991	4.006	4.009	4.018	4.038	4.007	4.011	4.019	4.004
% An	0.39	3.40	0.10	2.13	2.15	0.10	0.09	0.10	5.50	5.06	14.7	12.5	15.5	14.2	15.7

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	18	18	18	18	11	11	11	11	11	11	11	10	10	11	11	18	11
SiO_2	48.99	49.59	49.42	49.06	48.75	49.40	49.18	48.55	50.14	51.66	51.68	50.58	50.29	49.57	49.26	50.21	49.22
TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al_2O_3	52.96	52.52	53.56	53.29	53.31	53.05	53.27	54.00	52.96	52.85	51.55	52.35	52.51	53.04	52.94	52.75	54.04
FeO	1.61	1.89	0.88	0.85	0.88	0.79	0.94	0.71	0.90	0.82	0.82	0.97	1.26	0.90	0.78	0.91	0.89
MgO	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	14.97	15.32	14.80	14.99	15.80	15.46	14.66	14.99	14.01	12.56	12.58	14.90	15.18	14.42	14.14	13.84	14.07
Na_2O	2.99	2.61	2.45	2.54	2.14	2.05	2.22	2.24	2.57	2.77	5.15	2.67	2.60	2.44	2.57	2.67	2.27
K_2O	0.12	0.11	0.10	0.12	0.10	0.11	0.13	0.14	0.15	0.17	0.25	0.18	0.18	0.13	0.16	0.12	0.11
P_2O_5	0.14	0.14	0.18	0.19	0.18	0.09	0.07	0.18	0.15	0.14	0.10	0.10	0.07	0.12	0.14	0.15	0.11
Total	101.19	100.20	101.58	100.85	101.14	100.95	100.46	100.82	100.87	100.79	100.09	101.75	102.09	100.65	99.75	100.64	101.51
Si	2.221	2.262	2.226	2.223	2.206	2.256	2.255	2.199	2.263	2.515	2.540	2.277	2.298	2.245	2.247	2.270	2.212
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.762	1.748	1.782	1.777	1.778	1.765	1.781	1.814	1.755	1.735	1.682	1.711	1.720	1.764	1.772	1.744	1.805
Fe	0.060	0.071	0.051	0.052	0.055	0.029	0.055	0.026	0.055	0.050	0.050	0.055	0.046	0.055	0.029	0.055	0.055
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.727	0.650	0.715	0.727	0.767	0.749	0.715	0.727	0.676	0.595	0.610	0.712	0.729	0.699	0.691	0.669	0.716
Na	0.209	0.250	0.212	0.205	0.187	0.179	0.194	0.196	0.225	0.240	0.275	0.252	0.225	0.214	0.209	0.255	0.198
K	0.006	0.005	0.005	0.006	0.005	0.005	0.006	0.008	0.006	0.009	0.015	0.009	0.009	0.006	0.008	0.006	0.005
P	0.005	0.005	0.006	0.006	0.006	0.002	0.002	0.006	0.004	0.005	0.002	0.002	0.002	0.004	0.005	0.004	0.004
Total	4.990	4.970	4.976	4.976	4.982	4.965	4.967	4.977	4.959	4.926	4.951	4.978	4.990	4.965	4.961	4.959	4.970
Al + Si	3.983	4.010	4.008	4.000	3.984	3.999	4.016	4.015	4.016	4.050	4.022	3.988	3.978	4.009	4.019	4.014	4.015
X _{Al}	77.2	75.4	76.7	77.5	80.0	80.5	78.1	78.1	74.5	70.4	68.1	74.7	75.7	76.1	76.1	75.7	77.9

2R	2R	2R	2R	2I	2I	2C	2C	3,R,GM	3,R,GM	3,C,GM	4,GM	4,GM	4,GM	4,GM	4,GM	4,GM
49.63	49.92	49.80	49.35	47.79	47.84	48.95	47.98	50.29	50.10	48.79	49.91	50.95	49.16	49.45	49.49	49.21
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33.09	32.67	32.45	32.61	35.01	34.47	34.38	33.88	33.32	33.26	33.82	33.06	32.54	32.58	33.75	32.75	32.98
1.09	0.79	1.53	0.84	0.84	0.93	0.97	0.81	0.80	0.93	0.80	1.01	0.98	1.00	0.92	0.85	0.92
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15.52	14.51	13.77	14.34	15.76	16.09	15.27	15.72	14.69	15.03	15.01	14.14	13.54	14.12	15.10	13.91	13.78
2.40	2.32	2.76	2.37	1.64	1.47	1.96	1.73	2.83	2.51	2.04	2.64	2.92	2.52	2.34	2.27	2.30
0.09	0.05	0.08	0.07	0.10	0.07	0.10	0.05	0.11	0.09	0.10	0.11	0.09	0.05	0.13	0.08	0.05
0.09	0.12	0.14	0.14	0.16	0.23	0.13	0.18	0.16	0.18	0.12	0.13	0.13	0.14	0.15	0.18	0.16
101.91	100.38	100.54	99.72	101.32	101.11	101.77	100.36	102.21	102.09	100.68	101.00	101.14	99.57	101.84	99.54	99.40
2.231	2.263	2.262	2.255	2.159	2.167	2.197	2.186	2.249	2.241	2.212	2.253	2.290	2.251	2.219	2.259	2.250
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.753	1.746	1.737	1.756	1.864	1.840	1.819	1.818	1.755	1.753	1.808	1.759	1.724	1.758	1.784	1.762	1.778
0.041	0.029	0.057	0.031	0.032	0.034	0.035	0.030	0.029	0.034	0.029	0.037	0.035	0.038	0.034	0.032	0.035
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.747	0.704	0.669	0.701	0.762	0.780	0.733	0.767	0.703	0.719	0.729	0.683	0.651	0.692	0.726	0.681	0.675
0.208	0.203	0.242	0.209	0.143	0.129	0.170	0.152	0.244	0.216	0.178	0.230	0.253	0.223	0.203	0.199	0.202
0.004	0.002	0.004	0.004	0.005	0.004	0.005	0.002	0.005	0.004	0.005	0.005	0.004	0.002	0.006	0.004	0.002
0.002	0.004	0.005	0.005	0.005	0.008	0.004	0.006	0.005	0.006	0.004	0.004	0.004	0.005	0.005	0.006	0.005
4.986	4.951	4.976	4.960	4.970	4.963	4.964	4.963	4.989	4.974	4.964	4.971	4.961	4.969	4.977	4.943	4.947
3.984	4.009	3.999	4.011	4.023	4.007	4.016	4.004	4.004	3.994	4.020	4.012	4.014	4.009	4.003	4.021	4.028
77.9	77.4	73.1	76.7	83.7	85.4	80.7	83.3	73.5	76.6	79.9	74.4	71.7	75.5	77.6	77.0	76.8

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189 H

4, A, GM	5R	51	50	50	50	50	51	5R
49.69	52.29	50.07	53.23	54.55	49.57	49.92	54.52	52.95
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
32.94	29.57	30.91	32.57	31.07	30.68	29.79	29.44	29.86
0.95	1.20	0.85	1.10	0.87	1.16	1.10	0.93	1.14
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.10	12.61	14.43	11.59	11.63	13.42	15.04	10.60	13.02
2.49	3.61	2.95	3.80	4.32	2.84	2.71	4.45	3.68
0.08	0.23	0.20	0.16	0.23	0.19	0.17	0.31	0.25
0.14	0.11	0.15	0.11	0.14	0.13	0.13	0.07	0.11
100.39	99.61	99.57	102.55	102.81	98.00	98.86	100.32	101.02
2.254	2.386	2.298	2.346	2.399	2.306	2.313	2.452	2.384
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.761	1.591	1.672	1.691	1.611	1.682	1.626	1.560	1.584
0.034	0.045	0.032	0.040	0.031	0.043	0.042	0.034	0.042
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.684	0.616	0.710	0.547	0.547	0.669	0.746	0.510	0.627
0.218	0.318	0.261	0.324	0.368	0.255	0.243	0.386	0.321
0.004	0.013	0.011	0.007	0.011	0.011	0.009	0.017	0.014
0.005	0.004	0.005	0.003	0.005	0.004	0.004	0.001	0.004
4.960	4.974	4.990	4.959	4.972	4.971	4.983	4.960	4.976
4.015	3.977	3.970	4.037	4.010	3.988	3.939	4.012	3.968
75.5	65.0	72.3	62.3	59.1	71.6	74.7	55.9	65.2

	11	10	10	10	2R	21	2R	21	21	21	21	21	20	20
SiO ₂	52.64	50.02	52.65	55.49	57.92	52.86	57.86	52.61	54.16	52.54	54.21	53.80	54.98	54.19
TiO ₂	-	-	-	-	0.01	0.00	0.00	0.01	0.03	0.00	0.04	0.03	0.00	0.00
Al ₂ O ₃	28.74	30.54	28.13	28.63	25.93	30.60	25.71	29.98	30.07	28.30	28.76	28.84	29.31	28.59
FeO	0.79	0.65	0.52	0.70	0.90	0.90	0.80	0.97	1.05	1.12	0.80	0.88	0.81	0.80
MgO	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	10.23	9.78	10.05	9.62	7.80	11.98	7.19	12.47	10.77	10.88	10.45	10.74	10.63	10.79
Na ₂ O	8.27	9.33	8.05	4.76	6.93	4.53	6.94	4.63	5.16	5.05	5.13	5.25	5.21	5.07
K ₂ O	0.37	0.22	0.16	0.50	0.41	0.33	0.84	0.38	0.34	0.39	0.41	0.42	0.34	0.37
P ₂ O ₅	-	-	-	-	0.02	0.19	0.05	0.10	0.10	0.11	0.16	0.10	0.14	0.07
Total	101.03	100.54	99.57	99.69	99.92	101.38	99.38	101.14	101.69	98.39	99.97	100.05	101.43	99.89
Si	2.394	2.296	2.418	2.500	2.606	2.368	2.617	2.373	2.417	2.426	2.452	2.440	2.451	2.456
Ti	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Al	1.540	1.652	1.523	1.520	1.374	1.616	1.369	1.593	1.581	1.541	1.533	1.542	1.540	1.526
Fe	0.029	0.024	0.019	0.025	0.033	0.033	0.029	0.036	0.038	0.042	0.029	0.032	0.030	0.029
Mg	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.498	0.481	0.495	0.464	0.375	0.574	0.348	0.602	0.514	0.538	0.505	0.521	0.507	0.524
Na	0.728	0.830	0.717	0.415	0.603	0.398	0.607	0.403	0.446	0.453	0.448	0.460	0.450	0.445
K	0.021	0.012	0.009	0.027	0.022	0.018	0.047	0.021	0.018	0.021	0.022	0.024	0.018	0.021
P	-	-	-	-	0.000	0.006	0.001	0.002	0.002	0.004	0.005	0.002	0.004	0.001
Total	5.209	5.295	5.180	4.951	5.012	5.008	5.018	5.031	5.016	5.025	4.996	5.022	5.000	5.002
Al + Si	3.934	3.948	3.941	4.020	3.980	3.984	3.986	3.966	3.999	3.967	3.985	3.982	3.991	3.982
% An	39.9	36.4	40.5	51.2	37.5	58.0	34.7	58.7	52.6	53.2	51.8	51.8	52.0	52.9

ORIGINAL PAGE IS
OF POOR QUALITY

21	21	20	21	38	31	31	30	31
54.21	54.31	51.36	54.78	54.64	52.56	52.27	54.19	55.79
0.02	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00
29.14	28.91	30.64	30.42	28.85	29.08	28.97	29.31	28.76
0.89	0.84	1.10	1.14	0.86	0.79	0.99	1.01	1.04
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.21	10.80	12.30	8.84	10.07	11.30	10.65	11.29	9.77
5.04	5.13	4.21	6.02	5.50	4.70	5.09	5.45	6.06
0.35	0.38	0.25	0.28	0.30	0.38	0.29	0.36	0.11
0.10	0.11	0.14	0.05	0.09	0.07	0.10	0.07	0.09
100.96	100.48	100.02	101.54	100.32	98.88	98.37	101.67	101.61
2.435	2.446	2.339	2.435	2.462	2.413	2.413	2.424	2.480
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.542	1.534	1.646	1.592	1.532	1.573	1.575	1.544	1.507
0.033	0.031	0.041	0.042	0.031	0.029	0.038	0.037	0.038
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.539	0.521	0.600	0.420	0.485	0.555	0.525	0.541	0.464
0.439	0.448	0.372	0.518	0.480	0.417	0.455	0.472	0.521
0.020	0.021	0.013	0.016	0.017	0.021	0.016	0.020	0.005
0.002	0.004	0.004	0.001	0.002	0.001	0.002	0.002	0.002
5.010	5.005	5.015	5.023	5.010	5.010	5.024	5.040	5.018
3.977	3.980	3.985	4.027	3.994	3.986	3.988	3.968	3.987
54.0	52.6	60.9	44.0	49.4	55.9	52.7	52.4	46.9

66 B

	18	18	10	11	11	11	18	18	28	28	28	21	21	21	20	20	20
SiO_2	55.28	52.48	55.18	54.75	55.68	54.91	54.55	55.01	52.84	52.07	55.42	55.81	54.11	54.21	55.56	52.56	55.15
TiO_2	0.05	0.05	0.05	0.04	0.66	0.04	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.04	0.05	0.04	0.05
Al_2O_3	30.28	29.87	28.95	29.07	28.59	28.71	28.45	28.54	29.51	29.52	29.96	29.14	29.00	29.45	30.45	30.04	30.16
FeO	1.15	1.16	1.07	0.95	0.95	0.82	1.05	1.07	1.41	1.20	1.14	0.89	0.99	0.98	1.00	0.97	0.84
MgO	0.05	0.02	0.00	0.05	0.07	0.00	0.01	0.00	0.00	0.02	0.00	0.02	0.02	0.02	0.05	0.05	0.04
CaO	11.77	11.88	10.45	10.50	9.55	9.74	10.22	9.50	10.55	11.50	11.41	11.01	10.52	10.94	11.66	11.52	10.98
Na_2O	4.50	4.49	4.78	4.80	5.21	5.40	5.19	5.39	4.65	4.25	4.55	4.67	4.82	4.92	4.20	4.54	4.50
K_2O	0.16	0.14	0.29	0.25	0.27	0.26	0.12	0.12	0.09	0.09	0.11	0.18	0.19	0.17	0.21	0.26	0.14
P_2O_5	0.01	0.07	0.05	0.05	0.10	0.05	0.00	0.00	0.01	0.00	0.00	0.05	0.01	0.02	0.10	0.02	0.02
Total	101.16	100.15	98.75	100.45	101.07	99.94	99.60	99.72	98.88	98.46	100.61	99.80	99.69	100.75	101.05	99.61	99.82
Si	2.592	2.582	2.457	2.459	2.485	2.474	2.471	2.406	2.402	2.538	2.408	2.419	2.454	2.455	2.594	2.592	2.406
Ti	0.001	0.001	0.000	0.001	0.022	0.001	0.001	0.002	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.001	0.001
Al	1.599	1.597	1.565	1.558	1.501	1.524	1.520	1.519	1.614	1.602	1.591	1.556	1.550	1.558	1.609	1.610	1.609
Fe	0.042	0.044	0.040	0.054	0.054	0.050	0.059	0.040	0.054	0.046	0.042	0.035	0.037	0.035	0.037	0.036	0.032
Mg	0.001	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.002	0.002	0.001
Ca	0.565	0.577	0.511	0.504	0.455	0.469	0.495	0.460	0.504	0.557	0.550	0.554	0.511	0.526	0.560	0.551	0.535
Na	0.591	0.594	0.424	0.417	0.450	0.472	0.455	0.472	0.411	0.577	0.395	0.409	0.425	0.428	0.345	0.382	0.377
K	0.009	0.006	0.016	0.015	0.014	0.014	0.006	0.006	0.004	0.004	0.005	0.003	0.010	0.009	0.012	0.015	0.016
P	0.000	0.001	0.000	0.001	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000
Total	4.999	5.002	4.995	4.989	4.945	4.986	4.988	4.985	4.992	4.985	4.992	4.982	4.984	4.992	4.981	4.985	4.975
$\text{Al} + \text{Si}$	5.991	5.979	4.462	5.977	5.944	5.998	5.991	4.405	4.416	4.400	5.999	5.995	4.404	5.995	4.405	4.402	4.415
X_{Al}	58.5	59.1	55.7	54.0	49.5	49.1	51.8	49.0	59.0	59.4	57.8	56.1	54.1	54.6	59.8	56.1	57.6

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66 B

3,R,GM	3,R,GM	3,C,GM	3,C,GM	3,C,GM	4R	4R	4R	4I	4I	4C	4C
52.16	54.59	54.61	54.64	54.54	55.33	54.93	54.36	54.12	54.72	53.88	54.63
0.05	0.04	0.05	0.04	0.03	0.01	0.03	0.02	0.05	0.04	0.05	0.04
30.63	28.73	30.26	28.91	29.64	29.51	30.13	27.91	29.88	29.36	30.02	30.15
1.18	1.00	0.82	0.82	0.94	0.93	0.82	0.86	1.04	0.93	0.80	0.85
0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.01	0.00	0.03	0.02	0.02
10.76	10.37	10.54	10.14	10.42	9.56	10.51	10.81	11.06	11.16	11.09	10.98
4.50	4.77	4.70	4.78	4.59	4.79	4.66	4.84	4.45	4.64	4.79	4.74
0.13	0.13	0.17	0.24	0.17	0.11	0.08	0.11	0.28	0.32	0.32	0.30
0.07	0.03	0.07	0.03	0.05	0.00	0.07	0.02	0.00	0.02	0.00	0.05
99.48	99.66	101.25	99.65	100.38	100.25	101.22	98.93	100.87	101.23	100.98	101.76
2.375	2.471	2.431	2.471	2.449	2.479	2.444	2.483	2.426	2.445	2.417	2.425
0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001
1.643	1.532	1.587	1.540	1.567	1.557	1.580	1.502	1.579	1.545	1.587	1.577
0.044	0.037	0.030	0.030	0.034	0.034	0.030	0.032	0.038	0.034	0.029	0.031
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001
0.524	0.502	0.501	0.490	0.500	0.458	0.500	0.528	0.530	0.533	0.532	0.522
0.396	0.417	0.405	0.417	0.399	0.415	0.400	0.429	0.387	0.401	0.416	0.407
0.006	0.006	0.009	0.013	0.009	0.005	0.004	0.005	0.016	0.017	0.018	0.017
0.001	0.000	0.002	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.001
4.990	4.966	4.966	4.962	4.960	4.948	4.958	4.979	4.977	4.977	5.000	4.981
4.018	4.003	4.018	4.011	4.016	4.036	4.024	3.985	4.005	3.990	4.004	4.002
56.6	54.3	54.8	53.3	55.1	52.2	55.3	54.9	56.8	56.0	55.1	55.2

	2I	2I	2R	2C	4C	4C	4R	5,GM	6,GM,C	6,GM,R	7,GM,R
SiO ₂	55.68	55.25	55.64	52.77	55.80	54.48	56.91	54.79	55.07	55.88	55.94
TiO ₂	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	28.85	28.67	29.11	30.00	29.68	29.43	26.96	29.04	27.61	27.95	27.93
FeO	0.68	0.66	0.61	0.67	0.75	0.80	0.91	0.86	0.67	0.68	1.16
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	9.67	9.67	9.18	12.33	10.13	10.13	8.89	10.04	9.38	9.60	9.20
Na ₂ O	5.43	5.07	5.46	4.38	5.32	5.24	5.93	5.09	5.57	5.40	5.55
K ₂ O	0.23	0.23	0.17	0.18	0.18	0.14	0.23	0.18	0.16	0.18	0.18
P ₂ O ₅	0.09	0.07	0.07	0.16	0.11	0.07	0.07	0.12	0.07	0.07	0.14
Total	100.62	99.64	100.23	100.50	101.95	100.29	99.90	100.10	98.54	99.75	100.11
Si	2.489	2.491	2.490	2.385	2.463	2.451	2.559	2.466	2.514	2.518	2.515
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.520	1.523	1.535	1.597	1.544	1.561	1.429	1.540	1.484	1.483	1.480
Fe	0.025	0.023	0.022	0.025	0.027	0.029	0.033	0.031	0.025	0.025	0.043
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.463	0.467	0.440	0.597	0.478	0.488	0.427	0.483	0.458	0.462	0.443
Na	0.470	0.443	0.474	0.383	0.455	0.457	0.517	0.443	0.493	0.472	0.483
K	0.012	0.013	0.009	0.009	0.009	0.008	0.012	0.009	0.009	0.009	0.009
P	0.002	0.002	0.002	0.005	0.003	0.001	0.001	0.004	0.002	0.001	0.005
Total	4.980	4.963	4.972	5.000	4.979	4.994	4.978	4.976	4.985	4.970	4.979
Al + Si	4.009	4.014	4.025	3.982	4.007	4.012	3.988	4.006	3.998	4.001	3.995
% An	49.0	50.6	47.7	60.4	50.7	51.2	44.7	51.7	47.7	49.0	47.4

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OF POOR QUALITY

	1R	1R	1R	1I	1I	1C	1C	1C	1I	1I	1R	1A	2K	2K	3R	4C	4C
SiO ₂	65.01	65.42	61.83	54.44	55.30	54.79	54.29	54.98	57.43	59.93	58.70	57.76	65.34	64.18	61.45	56.34	55.05
TiO ₂	0.00	0.00	0.01	0.04	0.04	0.04	0.03	0.07	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.05
Al ₂ O ₃	23.20	23.18	23.00	28.91	29.12	28.76	28.82	28.55	27.17	25.03	25.97	26.68	19.17	19.00	23.78	28.06	28.45
FeO	0.55	0.48	0.56	0.98	0.96	1.23	1.26	1.07	1.03	0.44	0.66	0.80	0.46	0.45	0.58	0.90	0.56
MgO	0.00	0.00	0.00	0.00	0.00	0.05	0.02	0.05	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.07
CaO	3.86	3.75	3.89	9.57	9.79	10.05	10.13	9.56	8.23	5.91	6.88	7.64	0.06	0.07	5.09	9.18	9.29
Na ₂ O	8.51	8.72	8.77	5.26	5.09	5.19	5.10	4.96	6.11	7.46	8.07	6.66	1.77	1.60	8.02	5.45	5.57
K ₂ O	0.38	0.37	0.43	0.24	0.24	0.30	0.32	0.30	0.29	0.32	0.32	0.31	12.14	13.73	0.36	0.24	0.21
P ₂ O ₅	0.01	0.00	0.02	0.11	0.05	0.01	0.12	0.07	0.07	0.01	0.02	0.05	0.00	0.00	0.01	0.07	0.07
Total	99.52	99.92	98.52	99.55	100.59	100.42	100.11	99.62	100.34	99.11	100.62	99.91	98.96	99.04	99.28	100.27	99.32
Si	2.797	2.803	2.782	2.462	2.474	2.466	2.454	2.486	2.567	2.689	2.619	2.590	2.995	2.971	2.748	2.524	2.492
Ti	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Al	1.212	1.207	1.218	1.541	1.534	1.525	1.535	1.521	1.431	1.323	1.365	1.410	1.035	1.037	1.253	1.481	1.517
Fe	0.020	0.017	0.021	0.036	0.035	0.044	0.046	0.040	0.038	0.016	0.023	0.029	0.017	0.016	0.021	0.033	0.020
Mg	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
Ca	0.184	0.176	0.187	0.463	0.468	0.484	0.489	0.463	0.394	0.283	0.329	0.367	0.002	0.002	0.244	0.440	0.450
Na	0.732	0.747	0.764	0.460	0.441	0.452	0.447	0.435	0.528	0.649	0.698	0.578	0.156	0.143	0.694	0.472	0.489
K	0.021	0.021	0.023	0.013	0.013	0.017	0.019	0.017	0.016	0.017	0.017	0.017	0.001	0.000	0.000	0.002	0.001
P	0.000	0.000	0.000	0.004	0.001	0.000	0.004	0.001	0.002	0.000	0.000	0.000	0.001	0.000	0.000	0.002	0.001
Total	4.965	4.970	4.996	4.980	4.967	4.993	4.994	4.966	4.976	4.977	5.050	4.991	4.914	4.980	4.978	4.966	4.984
Al + Si	4.009	4.010	4.000	4.003	4.008	3.991	3.989	4.007	3.998	4.012	3.984	4.000	4.030	4.008	4.001	4.005	4.009
% An	19.6	18.6	19.2	49.5	50.8	50.8	51.2	50.6	42.0	29.8	31.5	38.2	0.23	0.21	25.5	47.6	47.3

4I	4I	4I	4I	4I	4I	4I	4I	4R	4A	5, GM	6, GM
54.37	54.25	60.33	58.54	56.50	59.53	58.43	58.57	61.59	57.25	63.83	54.64
0.04	0.03	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.00
28.81	28.61	25.60	25.21	28.97	25.69	25.36	25.61	23.96	27.27	22.73	29.00
0.74	1.02	0.92	0.48	0.62	0.45	0.62	0.66	0.41	0.70	0.27	0.89
0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
9.52	9.37	5.87	5.06	7.77	5.48	6.11	5.63	4.24	7.59	3.31	8.68
5.23	5.07	7.50	7.18	6.07	7.02	7.04	7.06	8.29	6.29	8.85	5.25
0.19	0.20	0.42	0.39	0.22	0.39	0.30	0.29	0.28	0.27	0.32	0.23
0.10	0.11	0.02	0.00	0.11	0.09	0.02	0.05	0.01	0.07	0.00	0.12
98.99	98.66	100.66	96.88	100.29	98.67	97.88	97.87	98.79	99.45	99.30	98.83
2.470	2.474	2.674	2.680	2.518	2.675	2.659	2.660	2.757	2.573	2.829	2.480
0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.542	1.537	1.337	1.359	1.521	1.359	1.359	1.370	1.264	1.444	1.188	1.552
0.028	0.039	0.034	0.017	0.022	0.016	0.022	0.024	0.014	0.025	0.009	0.033
0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.462	0.458	0.278	0.247	0.370	0.264	0.296	0.273	0.202	0.365	0.156	0.422
0.459	0.448	0.644	0.637	0.524	0.610	0.620	0.621	0.718	0.547	0.759	0.462
0.010	0.010	0.023	0.022	0.012	0.022	0.017	0.016	0.016	0.014	0.017	0.013
0.002	0.004	0.000	0.000	0.004	0.002	0.000	0.001	0.000	0.001	0.000	0.004
4.976	4.969	4.989	4.963	4.971	4.949	4.974	4.965	4.971	4.970	4.957	4.966
4.012	4.011	4.011	4.039	4.039	4.034	4.018	4.030	4.021	4.017	4.017	4.032
49.6	50.0	29.4	27.3	40.8	29.5	31.7	24.8	21.6	39.4	16.7	47.0

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	1R	1R	1R	1I	1I	1I	1I	1I	1C	1C	1C	1C	1C	1C	1C	2K	3K
SiO ₂	62.67	62.57	62.30	60.03	55.13	53.46	55.16	54.16	54.73	52.74	58.95	54.42	52.41	51.62	53.59	65.47	65.35
TiO ₂	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.01	0.00
Al ₂ O ₃	23.35	23.46	23.23	25.62	29.46	29.66	29.35	30.32	29.34	30.68	26.01	28.73	30.20	30.35	30.16	19.59	19.91
FeO	0.82	0.78	0.88	0.59	0.57	0.60	0.63	0.71	0.60	0.63	0.63	0.82	1.54	0.67	1.62	0.33	0.43
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	4.44	4.48	4.58	6.20	9.93	11.10	10.18	11.19	10.39	11.73	6.32	10.48	12.68	12.00	12.16	0.17	0.36
Na ₂ O	7.93	7.61	8.04	6.86	4.83	4.41	4.60	4.48	4.50	3.95	6.63	4.62	3.83	3.86	4.17	2.83	3.29
K ₂ O	0.59	0.57	0.54	0.42	0.25	0.26	0.27	0.24	0.30	0.21	0.50	0.24	0.24	0.18	0.19	12.19	12.38
P ₂ O ₅	0.01	0.00	0.01	0.00	0.05	0.10	0.07	0.14	0.07	0.07	0.00	0.05	0.05	0.12	0.12	0.00	0.00
Total	99.81	99.48	99.59	99.73	100.24	99.58	100.27	101.25	99.93	100.04	99.02	99.38	100.96	98.89	102.01	100.58	101.68
Si	2.783	2.784	2.775	2.676	2.470	2.424	2.472	2.417	2.462	2.384	2.650	2.468	2.366	2.365	2.390	2.966	2.939
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.222	1.229	1.220	1.346	1.556	1.584	1.550	1.595	1.555	1.634	1.377	1.536	1.607	1.639	1.585	1.045	1.055
Fe	0.030	0.028	0.031	0.021	0.021	0.022	0.022	0.026	0.022	0.022	0.022	0.030	0.057	0.025	0.060	0.012	0.016
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.211	0.212	0.218	0.295	0.476	0.539	0.488	0.534	0.500	0.567	0.303	0.508	0.613	0.589	0.581	0.008	0.017
Na	0.681	0.657	0.694	0.592	0.419	0.387	0.399	0.386	0.392	0.345	0.576	0.406	0.335	0.341	0.360	0.247	0.287
K	0.032	0.031	0.030	0.023	0.014	0.014	0.014	0.013	0.017	0.012	0.027	0.013	0.013	0.009	0.010	0.703	0.710
P	0.000	0.000	0.000	0.000	0.001	0.002	0.002	0.005	0.001	0.002	0.000	0.001	0.001	0.004	0.004	0.000	0.000
Total	4.958	4.942	4.968	4.954	4.958	4.973	4.948	4.976	4.950	4.967	4.956	4.963	4.992	4.973	4.990	4.980	5.024
Al + Si	4.005	4.013	3.995	4.022	4.026	4.008	4.022	4.012	4.017	4.018	4.027	4.004	3.973	4.004	3.975	4.011	3.994
% An	22.8	23.6	23.1	32.4	52.4	57.3	54.2	57.2	55.0	61.4	33.4	54.8	63.8	62.7	61.1	0.84	1.68

ORIGINAL PAGE IS
OF POOR QUALITY

181

4, GM	4K	5, GM	5K	5K
61.79	65.12	62.50	64.13	64.85
0.00	0.00	0.00	0.00	0.00
24.87	18.92	23.09	19.01	19.05
0.59	0.39	0.71	0.43	0.31
0.00	0.00	0.00	0.00	0.00
5.68	0.13	4.43	0.20	0.25
7.80	3.06	8.81	2.53	2.87
0.44	11.77	0.58	11.95	12.02
0.00	0.00	0.00	0.00	0.00
101.16	99.39	100.12	98.24	99.34
2.717	2.982	2.776	2.972	2.976
0.000	0.000	0.000	0.000	0.000
1.287	1.020	1.208	1.038	1.030
0.021	0.015	0.026	0.016	0.011
0.000	0.000	0.000	0.000	0.000
0.267	0.005	0.209	0.009	0.011
0.664	0.271	0.758	0.227	0.254
0.024	0.687	0.032	0.706	0.703
0.000	0.000	0.000	0.000	0.000
4.979	4.979	5.010	4.967	4.984
4.004	4.002	3.984	4.010	4.006
28.0	0.52	20.9	0.96	1.14

U5-188

	1C	1I	2,001	2I	2I	2I	2I	20	2I	2I	2I	2I	2I	2R	3R	3R	3I
SiO ₂	53.23	57.86	53.54	53.59	52.72	54.20	54.43	53.98	54.32	53.66	57.53	54.30	54.04	61.07	61.50	62.14	52.55
TiO ₂	0.07	0.04	0.09	0.03	0.04	0.05	0.04	0.04	0.04	0.03	0.01	0.10	0.09	0.03	0.03	0.00	0.04
Al ₂ O ₃	30.08	27.56	27.78	29.59	28.95	28.41	28.24	28.01	28.01	28.74	25.93	29.11	29.18	25.36	24.14	25.08	30.43
FeO	0.96	0.86	0.81	1.00	1.04	0.95	1.03	1.10	1.14	1.13	0.94	0.82	0.93	0.71	0.75	0.64	0.99
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	10.92	7.29	10.91	11.12	10.11	10.03	9.49	10.43	9.44	10.28	7.08	9.84	10.60	4.79	4.52	4.25	11.63
Na ₂ O	4.99	6.61	5.25	5.00	4.98	5.48	5.84	5.50	5.50	5.06	6.96	5.38	5.23	8.81	8.36	8.89	4.67
K ₂ O	0.23	0.42	0.31	0.28	0.32	0.38	0.42	0.38	0.33	0.30	0.63	0.38	0.30	0.60	0.57	0.54	0.28
P ₂ O ₅	0.07	0.03	0.07	0.09	0.11	0.10	0.09	0.07	0.07	0.07	0.05	0.07	0.07	0.02	0.05	0.01	0.14
Total	100.53	100.69	98.76	100.74	98.28	99.61	99.59	99.49	98.84	99.28	99.13	100.01	100.64	101.39	99.92	101.36	100.67
Si	2.400	2.574	2.459	2.415	2.426	2.462	2.473	2.459	2.481	2.447	2.606	2.453	2.434	2.689	2.737	2.720	2.372
Ti	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.002	0.002	0.000	0.000	0.000	0.001
Al	1.599	1.445	1.503	1.571	1.569	1.521	1.512	1.504	1.508	1.544	1.384	1.550	1.549	1.315	1.265	1.293	1.616
Fe	0.036	0.031	0.031	0.037	0.039	0.036	0.039	0.041	0.042	0.042	0.034	0.030	0.034	0.025	0.027	0.023	0.037
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.526	0.347	0.537	0.536	0.498	0.488	0.461	0.509	0.461	0.501	0.343	0.476	0.521	0.226	0.214	0.199	0.562
Na	0.435	0.570	0.466	0.436	0.444	0.482	0.515	0.485	0.486	0.447	0.611	0.470	0.456	0.752	0.721	0.754	0.403
K	0.013	0.023	0.017	0.016	0.019	0.021	0.024	0.021	0.019	0.017	0.036	0.021	0.017	0.033	0.031	0.029	0.016
P	0.001	0.000	0.002	0.002	0.004	0.002	0.002	0.001	0.001	0.002	0.001	0.002	0.002	0.000	0.001	0.000	0.005
Total	5.011	4.992	5.018	5.015	5.000	5.013	5.026	5.022	5.000	5.001	5.015	5.004	5.016	5.041	4.996	5.013	5.015
Al + Si	3.999	4.019	3.962	3.986	3.995	3.983	3.985	3.963	3.989	3.991	3.990	4.003	3.983	4.004	4.002	4.013	3.988
% An	54.0	36.9	52.6	54.3	51.8	49.2	46.1	50.1	47.7	51.9	34.6	49.2	52.4	22.3	22.2	20.3	57.0

U5-188

3I	3I	3I	3I	3G	3G	3G	3G	3G	4, C, GM	4, R, GM	5K	6K	7K	8K	9, GM	10, GM
52.62	56.37	52.31	52.87	50.24	48.72	49.44	51.64	51.75	52.98	61.29	63.51	64.48	63.33	62.99	57.48	59.73
0.09	0.03	0.04	0.05	0.07	0.05	0.02	0.07	0.09	0.04	0.03	0.02	0.01	0.03	0.03	0.02	0.00
29.41	27.95	32.39	30.38	30.47	32.09	31.76	30.89	30.54	30.30	24.77	19.38	19.50	19.05	19.22	26.39	25.09
0.80	1.00	1.16	0.95	0.60	0.86	0.86	0.95	0.83	1.16	0.75	0.43	0.42	0.39	0.20	0.74	0.46
0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.81	9.43	10.64	11.43	13.19	14.24	13.99	11.60	11.95	11.69	4.60	0.25	0.23	0.11	0.18	6.88	5.77
5.14	6.46	4.40	4.52	3.24	2.56	3.08	4.51	4.33	4.81	8.18	2.97	2.79	1.55	2.05	7.11	7.27
0.33	0.49	0.19	0.25	0.23	0.13	0.21	0.23	0.28	0.20	0.50	12.79	12.93	14.88	15.15	0.47	0.34
0.10	0.14	0.16	0.10	0.16	0.12	0.09	0.11	0.10	0.09	0.01	0.01	0.01	0.01	0.03	0.07	0.00
99.30	101.86	101.33	100.55	98.41	98.77	99.45	100.00	99.88	101.27	100.13	99.34	100.37	99.35	99.84	99.17	98.66
2.405	2.505	2.335	2.385	2.325	2.251	2.272	2.346	2.357	2.378	2.720	2.938	2.948	2.948	2.929	2.597	2.688
0.002	0.000	0.001	0.001	0.001	0.001	0.000	0.001	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.584	1.463	1.705	1.615	1.662	1.747	1.719	1.654	1.639	1.604	1.296	1.055	1.050	1.045	1.053	1.405	1.330
0.029	0.036	0.043	0.036	0.030	0.032	0.032	0.034	0.030	0.043	0.027	0.016	0.015	0.015	0.006	0.028	0.017
0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.528	0.448	0.508	0.552	0.653	0.705	0.688	0.563	0.583	0.561	0.219	0.011	0.010	0.004	0.008	0.333	0.277
0.455	0.557	0.380	0.394	0.291	0.229	0.273	0.397	0.382	0.419	0.703	0.266	0.247	0.139	0.184	0.623	0.634
0.019	0.027	0.010	0.013	0.012	0.006	0.012	0.012	0.016	0.010	0.027	0.753	0.753	0.884	0.897	0.026	0.018
0.002	0.004	0.005	0.002	0.005	0.004	0.002	0.004	0.002	0.002	0.000	0.000	0.000	0.000	0.000	0.002	0.000
5.025	5.041	4.989	4.998	4.979	4.976	4.999	5.012	5.011	5.019	4.932	5.041	5.022	5.034	5.078	5.015	4.965
3.989	3.968	4.040	4.000	3.987	3.998	3.991	4.000	3.996	3.982	4.016	3.994	3.998	3.993	3.982	4.002	4.018
52.7	43.4	56.6	57.6	68.3	75.0	70.7	57.9	59.4	56.7	23.1	1.07	0.99	0.39	0.74	33.9	29.8

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	1R	1R	1R	1I	1I	1I	1I	1I	1I	1I	1I	1I	1I	1I	1I
SiO ₂	59.23	59.41	59.32	59.50	59.49	58.15	57.60	56.27	54.41	55.20	53.42	54.34	59.26	56.34	56.04
TiO ₂	0.05	0.03	0.05	0.01	0.03	0.07	0.04	0.04	0.04	0.04	0.05	0.04	0.03	0.05	0.03
Al ₂ O ₃	25.41	25.04	25.72	25.69	26.13	26.29	27.49	28.24	28.37	29.07	29.81	29.25	25.68	27.25	28.18
FeO	0.61	0.65	0.81	0.55	0.77	0.59	0.70	0.68	0.62	0.73	0.68	0.68	0.61	0.45	0.51
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	6.32	6.18	6.62	6.61	6.93	8.16	8.82	9.37	10.84	10.30	11.38	11.14	6.79	9.29	8.70
Na ₂ O	7.87	7.95	7.71	6.93	7.33	6.69	6.52	5.91	5.31	5.41	4.78	5.13	7.32	6.29	6.14
K ₂ O	0.49	0.45	0.45	0.66	0.65	0.55	0.38	0.39	0.32	0.34	0.29	0.30	0.64	0.41	0.39
P ₂ O ₅	0.00	0.00	0.00	0.02	0.03	0.01	0.02	0.05	0.05	0.09	0.03	0.07	0.01	0.05	0.05
Total	99.98	99.70	100.69	99.97	101.35	100.51	101.56	100.95	99.99	101.20	100.45	100.96	100.34	100.14	100.04
Si	2.651	2.666	2.637	2.657	2.631	2.600	2.552	2.509	2.461	2.464	2.410	2.437	2.643	2.535	2.518
Ti	0.001	0.000	0.001	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.000
Al	1.340	1.325	1.348	1.352	1.361	1.384	1.435	1.484	1.512	1.528	1.585	1.546	1.350	1.444	1.491
FeO	0.022	0.023	0.030	0.020	0.027	0.021	0.024	0.024	0.022	0.026	0.025	0.025	0.022	0.016	0.018
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.302	0.296	0.314	0.315	0.328	0.391	0.417	0.447	0.527	0.492	0.549	0.534	0.325	0.447	0.418
Na	0.682	0.691	0.664	0.599	0.628	0.578	0.559	0.510	0.464	0.467	0.417	0.444	0.632	0.548	0.535
K	0.027	0.025	0.024	0.037	0.036	0.030	0.021	0.022	0.017	0.018	0.016	0.017	0.035	0.023	0.022
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.002	0.000	0.002	0.000	0.001	0.001
Total	5.024	5.026	5.019	4.979	5.011	5.003	0.009	4.999	5.006	4.999	5.003	5.007	5.007	5.015	5.003
Al + Si	3.991	3.991	3.985	4.009	3.922	3.984	3.987	3.993	0.973	3.992	3.995	3.983	3.993	3.979	4.009
% An	29.9	29.2	31.3	33.1	33.1	39.1	41.8	45.7	52.3	50.3	55.9	53.7	32.8	43.9	42.9

1R	1R	2,C,GM	2,C,GM	2,C,GM	2,R,GM	2,I,GM	2,R,GM	2,R,GM	3C	3C	3I	3I	3I	3R
60.01	60.94	55.16	55.29	55.29	59.98	59.70	59.50	60.07	54.16	53.05	54.64	53.55	54.58	61.17
0.05	0.04	0.05	0.07	0.07	0.05	0.03	0.04	0.03	0.04	0.04	0.04	0.07	0.01	0.04
25.50	24.80	28.68	28.25	28.25	25.28	25.21	25.25	26.15	30.17	29.14	29.41	29.96	28.61	24.76
0.63	0.72	1.69	0.96	0.96	0.59	0.75	0.38	0.61	0.82	0.80	0.71	0.92	0.76	0.47
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.48	5.94	10.11	9.75	9.75	6.13	6.04	6.09	6.64	11.33	12.23	10.85	11.34	10.25	5.48
7.18	7.66	5.63	5.86	5.86	7.70	7.70	7.52	7.61	4.71	5.06	4.92	4.77	5.51	8.03
0.68	0.50	0.32	0.34	0.34	0.42	0.73	0.39	0.52	0.28	0.33	0.29	0.33	0.34	0.89
0.05	0.01	0.05	0.05	0.05	0.03	0.00	0.00	0.01	0.10	0.10	0.05	0.05	0.11	0.00
100.57	100.70	101.70	100.57	100.57	100.18	100.17	99.16	101.65	101.61	100.75	100.92	101.00	100.18	100.85
2.663	2.699	2.462	2.486	2.486	2.672	2.668	2.673	2.644	2.413	2.402	2.445	2.404	2.463	2.706
0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.000	0.001	0.001	0.001	0.001	0.000	0.001
1.333	1.294	1.509	1.496	1.496	1.327	1.327	1.336	1.356	1.583	1.554	1.551	1.585	1.521	1.290
0.023	0.026	0.063	0.035	0.035	0.021	0.027	0.013	0.021	0.030	0.029	0.026	0.034	0.027	0.017
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.307	0.280	0.483	0.470	0.470	0.291	0.288	0.292	0.313	0.540	0.592	0.520	0.544	0.495	0.259
0.617	0.656	0.486	0.510	0.510	0.665	0.666	0.654	0.649	0.406	0.443	0.427	0.415	0.482	0.688
0.038	0.032	0.018	0.018	0.018	0.023	0.041	0.021	0.028	0.016	0.019	0.016	0.018	0.018	0.049
0.001	0.000	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.002	0.002	0.001	0.001	0.002	0.000
4.984	4.988	5.022	5.017	5.017	5.000	5.016	4.990	5.011	4.991	5.042	4.986	5.002	5.011	5.008
3.996	3.993	3.971	3.982	3.982	3.999	3.995	4.009	4.000	3.996	3.956	3.996	3.989	3.984	3.996
31.9	28.9	48.9	47.1	47.1	29.7	28.9	30.2	31.6	56.1	56.2	54.0	55.7	49.7	26.0

ORIGINAL PAGE IS
OF POOR QUALITY

179 E

3R	3I	3C	4K	5K	6K	7K	8K	AK
61.73	55.34	50.97	63.59	69.59	63.87	53.55	65.44	64.03
0.01	0.05	0.08	0.03	0.04	0.02	0.00	0.03	0.02
24.64	29.11	28.54	18.71	18.48	18.79	18.32	18.68	18.59
0.71	0.80	0.59	0.06	0.38	0.08	0.34	0.25	0.22
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.20	9.84	13.96	0.46	0.04	0.10	0.05	0.09	0.14
8.28	5.64	3.91	2.61	1.71	1.65	1.53	2.11	1.92
0.70	0.43	0.41	12.70	14.40	15.32	14.28	13.05	13.95
0.01	0.07	0.11	0.00	0.00	0.00	0.00	0.00	0.00
101.28	101.29	98.57	98.17	98.73	99.82	98.05	99.66	98.87
2.718	2.468	2.366	2.966	2.973	2.962	2.983	2.998	2.978
0.000	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.000
1.277	1.530	1.561	1.028	1.017	1.026	1.012	1.008	1.018
0.025	0.028	0.021	0.001	0.014	0.002	0.012	0.009	0.008
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.244	0.470	0.693	0.021	0.001	0.004	0.001	0.004	0.006
0.707	0.487	0.351	0.235	0.155	0.147	0.139	0.187	0.173
0.039	0.023	0.024	0.755	0.857	0.906	0.852	0.762	0.827
0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000	0.000
5.010	5.008	5.023	5.007	5.017	5.048	4.999	4.967	5.009
3.995	3.998	3.927	3.994	3.990	3.988	3.995	4.006	3.996
24.6	48.0	64.9	2.1	0.10	0.38	0.10	0.42	0.60

	1K	2K	3KG	3KR	3,GM	4,GM	5I	5C	5G	5H	7,R,GM	7,C,GM
SiO ₂	64.76	63.76	64.64	64.81	62.98	63.84	57.19	51.53	56.46	53.69	56.19	52.62
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.04	0.05	0.03	0.06
Al ₂ O ₃	19.92	19.89	20.27	19.98	25.34	23.88	28.21	30.34	27.99	28.73	28.40	29.91
FeO	0.08	0.48	0.23	0.25	0.34	0.08	0.30	0.18	0.25	0.29	0.22	0.25
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
CaO	0.12	0.08	0.06	0.04	4.41	3.72	8.49	10.05	8.50	8.97	5.15	9.89
Na ₂ O	2.40	1.32	1.28	0.98	5.88	8.54	6.84	6.97	8.36	8.25	10.87	7.81
K ₂ O	14.26	13.42	13.50	14.25	0.38	0.57	.30	.30	0.32	0.25	0.47	0.22
P ₂ O ₅	0.00	0.00	0.00	0.00	0.02	0.00	-	-	-	-	-	-
Total	101.54	98.95	99.98	100.33	99.35	100.63	101.38	99.41	101.91	100.22	101.33	100.79
Si	2.937	2.947	2.951	2.956	2.773	2.795	2.534	2.360	2.508	2.436	2.508	2.381
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001
Al	1.064	1.083	1.090	1.074	1.314	1.232	1.473	1.637	1.465	1.536	1.494	1.595
Fe	0.002	0.018	0.008	0.009	0.011	0.002	0.011	0.007	0.009	0.010	0.008	0.009
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ca	0.005	0.002	0.002	0.001	0.207	0.173	0.403	0.493	0.404	0.436	0.246	0.479
Na	0.210	0.116	0.112	0.085	0.501	0.725	0.588	0.618	0.719	0.725	0.940	0.685
K	0.824	0.791	0.785	0.828	0.021	0.031	0.016	0.017	0.017	0.014	0.026	0.012
P	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-	-
Total	5.042	4.957	4.948	4.954	4.826	4.959	5.029	5.137	5.126	5.163	5.226	5.168
Al + Si	4.001	4.030	4.041	4.030	4.087	4.027	4.007	3.997	3.973	3.972	4.002	3.976
% kn	0.48	0.22	0.22	0.11	28.4	18.6	40.0	43.7	35.4	37.1	20.3	40.7

ORIGINAL PAGE IS
OF POOR QUALITY

	1I	1I	1R	1R	2R	2I	2I	2C	2C	2C	2C
B ₂ O ₃	58.32	60.23	63.12	63.52	66.56	64.13	63.28	55.82	54.78	55.93	54.39
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Al ₂ O ₃	24.23	24.18	24.14	23.67	22.09	22.80	23.96	28.63	29.05	28.02	29.07
FeO	0.54	0.68	0.64	0.48	0.43	0.30	0.58	0.74	0.67	0.86	0.78
MgO	0.02	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.01
CaO	8.14	7.58	4.71	4.77	2.89	3.95	5.10	10.68	10.77	10.22	11.30
Na ₂ O	6.31	6.85	7.89	8.46	8.64	9.04	8.33	5.20	4.58	5.56	4.73
K ₂ O	0.64	0.55	0.55	0.58	0.57	0.30	0.49	0.29	0.27	0.34	0.24
F ₂ O ₅	0.00	0.03	0.00	0.03	0.00	0.02	0.03	0.05	0.01	0.14	0.05
Total	98.20	100.11	101.08	101.54	101.18	100.53	101.77	101.41	100.13	101.11	100.58
Si	2.661	2.693	2.766	2.776	2.887	2.817	2.762	2.484	2.466	2.500	2.446
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.302	1.274	1.246	1.218	1.129	1.180	1.232	1.500	1.540	1.475	1.541
Fe	0.020	0.025	0.023	0.017	0.015	0.010	0.020	0.027	0.025	0.031	0.029
Mg	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.397	0.362	0.221	0.223	0.133	0.186	0.238	0.509	0.519	0.489	0.543
Na	0.558	0.593	0.669	0.717	0.727	0.770	0.704	0.448	0.399	0.481	0.412
K	0.036	0.030	0.029	0.032	0.030	0.017	0.027	0.016	0.014	0.018	0.013
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.005	0.001
Total	4.976	4.976	4.954	4.983	4.921	4.979	4.983	4.986	4.963	4.999	4.984
Al + Si	3.963	3.967	4.012	3.994	4.016	3.997	3.994	3.984	4.006	3.975	3.987
% An	40.1	36.8	24.0	22.9	14.9	19.1	24.6	52.3	55.7	49.5	56.1

	1R	1I	1R	1R	2R	2I	2I	2I	20	2I	2I	2I	2I	2I
SiO ₂	66.58	59.24	63.47	63.47	64.26	60.02	60.23	59.83	59.52	60.33	62.46	62.11	60.24	60.13
TiO ₂	0.00	0.03	0.00	0.00	0.00	0.00	0.03	0.04	0.00	0.04	0.00	0.03	0.00	0.00
Al ₂ O ₃	23.12	26.74	25.01	24.16	24.63	25.39	25.29	26.44	25.64	25.79	23.32	24.25	24.68	25.41
FeO	0.19	0.73	0.60	0.39	0.50	0.63	0.62	0.65	0.64	0.46	0.36	0.39	0.45	0.51
HgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	3.05	8.04	4.83	4.43	3.97	5.34	6.06	6.63	6.86	6.28	3.55	4.12	4.91	5.72
Na ₂ O	7.35	6.18	7.53	7.96	7.68	7.34	7.27	6.86	6.93	6.85	8.37	8.10	7.73	7.22
K ₂ O	0.54	0.45	0.39	0.55	0.37	0.53	0.51	0.42	0.29	0.34	0.52	0.52	0.52	0.46
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.05	0.02	0.00	0.01	0.01	0.07
Total	100.84	101.40	101.82	100.96	101.41	99.27	100.02	100.92	99.93	100.11	98.58	99.53	98.54	99.53
Si	2.879	2.614	2.753	2.776	2.787	2.687	2.683	2.640	2.655	2.675	2.795	2.759	2.713	2.684
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000
Al	1.177	1.390	1.278	1.245	1.259	1.340	1.327	1.375	1.349	1.347	1.229	1.269	1.309	1.336
Fe	0.006	0.026	0.021	0.014	0.018	0.023	0.022	0.023	0.023	0.017	0.013	0.014	0.016	0.018
Hg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.141	0.379	0.224	0.207	0.183	0.255	0.283	0.312	0.327	0.298	0.169	0.195	0.236	0.272
Na	0.615	0.528	0.632	0.675	0.645	0.637	0.627	0.586	0.598	0.588	0.726	0.697	0.674	0.625
K	0.029	0.024	0.020	0.029	0.019	0.030	0.028	0.023	0.016	0.018	0.029	0.028	0.029	0.026
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.001
Total	4.847	4.961	4.928	4.946	4.911	4.972	4.976	4.961	4.969	4.943	4.961	4.963	4.977	4.962
Al + Si	4.056	4.004	4.031	4.021	4.046	4.027	4.010	4.015	4.004	4.022	4.024	4.028	4.022	4.020
% An	18.0	40.7	25.6	22.7	21.6	27.7	30.6	33.9	34.8	33.0	18.3	21.2	25.1	29.5

ORIGINAL PAGE IS
OF POOR QUALITY

2I	2I	2I	3K	3K	4I	4I	4G	4R	5,C,GM	5,R,GM	6K
63.40	58.42	61.45	65.91	64.26	55.11	54.36	55.88	55.05	58.91	61.82	63.57
0.00	0.05	0.03	0.04	0.04	0.07	0.08	0.12	0.11	0.05	0.00	0.04
22.95	26.50	25.20	19.78	19.63	28.74	29.19	28.60	28.37	25.48	24.44	19.56
0.16	0.55	0.58	0.17	0.38	0.39	0.63	0.65	0.69	0.50	0.32	0.22
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.22	6.98	5.01	0.08	0.14	9.88	10.01	10.01	9.81	7.13	5.36	0.05
8.60	6.65	8.03	3.23	2.63	5.18	5.24	5.12	5.54	6.59	7.68	1.76
0.40	0.30	0.40	11.47	12.25	0.18	0.46	0.27	0.30	0.29	0.40	14.03
0.00	0.05	0.08	0.01	0.25	0.12	0.05	0.10	0.05	0.00	0.05	0.00
98.73	99.52	100.79	100.69	99.59	99.61	100.02	100.76	99.92	98.95	100.07	99.28
2.824	2.616	2.708	2.970	2.942	2.485	2.454	2.496	2.485	2.652	2.735	2.943
0.000	0.001	0.000	0.001	0.001	0.001	0.002	0.004	0.002	0.001	0.000	0.001
1.203	1.398	1.309	1.050	1.059	1.527	1.553	1.505	1.509	1.352	1.273	1.066
0.005	0.020	0.021	0.005	0.013	0.014	0.022	0.023	0.025	0.018	0.011	0.009
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.153	0.335	0.236	0.002	0.006	0.476	0.483	0.479	0.474	0.343	0.253	0.001
0.742	0.577	0.685	0.281	0.232	0.447	0.458	0.443	0.484	0.575	0.658	0.157
0.022	0.017	0.022	0.658	0.714	0.009	0.026	0.014	0.017	0.016	0.022	0.827
0.000	0.001	0.002	0.000	0.009	0.004	0.001	0.002	0.001	0.000	0.001	0.000
4.949	4.964	4.983	4.968	4.977	4.962	5.000	4.966	4.998	4.956	4.953	5.005
4.027	4.014	4.017	4.020	4.001	4.012	4.007	4.001	3.994	4.004	4.008	4.009
16.7	36.1	25.0	0.21	0.63	51.1	49.9	51.2	48.6	36.7	27.1	0.10

	1R	1R	1G	1,GM	2R	2R	2I	2I	2I	2C	2C	2C	2,GM	3,GM	4,GM
SiO ₂	52.437	49.392	46.058	55.417	52.670	53.414	50.895	51.673	51.598	51.888	53.184	52.599	51.555	53.571	53.935
TiO ₂	0.118	0.116	0.078	0.102	0.103	0.130	0.103	0.108	0.133	0.107	0.095	0.103	0.098	0.125	0.099
Al ₂ O ₃	30.834	32.609	32.988	28.039	30.337	29.516	29.433	29.261	29.956	28.874	29.384	28.846	29.093	28.587	29.009
FeO	0.820	0.759	0.714	0.699	0.742	1.265	0.755	0.733	0.765	0.731	0.717	0.811	0.760	0.774	0.755
MnO	0.004	0.004	-	0.031	0.021	0.008	0.014	0.000	0.003	0.016	0.007	0.005	0.011	0.004	0.025
MgO	0.155	0.126	0.140	0.105	0.143	0.346	0.136	0.140	0.149	0.149	0.159	0.273	0.153	0.144	0.122
CaO	12.643	13.171	16.860	11.262	11.897	11.818	12.128	11.763	11.782	11.462	11.259	10.906	11.330	11.750	11.174
Na ₂ O	4.277	3.694	1.682	4.791	4.879	4.963	4.408	5.139	5.605	5.346	5.628	5.235	5.470	5.372	5.660
K ₂ O	0.364	0.286	0.064	0.417	0.405	0.394	0.372	0.429	0.398	0.431	0.458	0.472	0.392	0.341	0.375
Total	101.657	100.162	98.587	100.867	101.201	101.859	98.249	99.249	100.393	99.008	100.894	99.255	98.865	100.671	101.158
Si	2.351	2.253	2.198	2.486	2.370	2.393	2.362	2.376	2.351	2.391	2.402	2.411	2.380	2.424	2.426
Ti	0.004	0.004	0.002	0.003	0.003	0.004	0.003	0.003	0.004	0.003	0.003	0.003	0.003	0.004	0.003
Al	1.629	1.753	1.783	1.482	1.609	1.558	1.610	1.586	1.609	1.568	1.564	1.558	1.583	1.524	1.538
Fe	0.030	0.028	0.028	0.026	0.027	0.047	0.029	0.028	0.029	0.028	0.027	0.031	0.029	0.029	0.028
Mn	0.000	0.000	-	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.010	0.008	0.009	0.007	0.009	0.023	0.009	0.009	0.010	0.010	0.010	0.018	0.010	0.009	0.008
Ca	0.607	0.643	0.862	0.541	0.573	0.567	0.603	0.579	0.575	0.566	0.544	0.535	0.560	0.569	0.538
Na	0.371	0.326	0.155	0.416	0.425	0.431	0.396	0.458	0.495	0.477	0.492	0.465	0.489	0.471	0.493
K	0.020	0.016	0.003	0.023	0.023	0.022	0.022	0.025	0.023	0.025	0.026	0.027	0.023	0.019	0.021
Total	5.026	5.036	5.046	4.989	5.045	5.049	5.038	5.068	5.098	5.072	5.072	5.052	5.080	5.054	5.059
Al + Si	3.980	4.006	3.981	3.968	3.979	3.951	3.972	3.962	3.960	3.959	3.966	3.969	3.963	3.948	3.964
% An	60.8	65.3	84.5	55.2	56.1	55.6	59.1	54.5	52.6	53.0	51.2	52.1	52.2	53.7	51.1

ORIGINAL PAGE IS
OF POOR QUALITY

MK 3A

	1R	1I	1I	1I	1I	1C	1C	1C	1,GM	1,GM	R,GM	2C	3C	3R	3I	4C	4C
SiO ₂	55.70	57.61	59.04	58.96	59.14	53.85	54.71	53.19	55.34	57.24	54.75	58.07	55.64	55.15	56.21	54.77	56.53
TiO ₂	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.03	0.02	0.04	0.03	0.02	0.04	0.03
Al ₂ O ₃	27.43	27.04	26.75	26.21	26.08	28.96	27.79	28.66	28.00	27.19	27.17	26.19	27.86	27.34	27.80	27.39	27.23
FeO	0.90	0.46	0.31	0.39	0.33	0.65	0.48	0.59	0.96	1.63	1.05	0.39	0.45	1.09	0.40	1.33	1.00
MgO	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00
CaO	9.50	8.05	7.45	7.07	6.61	11.14	10.05	11.18	9.67	8.04	9.27	7.52	9.20	8.69	8.16	9.58	8.96
Na ₂ O	5.90	6.79	7.21	7.46	7.51	5.33	4.90	4.98	5.89	6.73	6.02	6.84	5.88	6.00	6.25	5.98	6.23
K ₂ O	0.19	0.24	0.25	0.24	0.29	0.14	0.20	0.17	0.17	0.26	0.28	0.23	0.20	0.27	0.21	0.13	0.23
P ₂ O ₅	0.03	0.00	0.01	0.00	0.00	0.05	0.05	0.00	0.03	0.00	0.01	0.03	0.03	0.02	0.00	0.07	0.03
Total	99.66	100.23	101.05	100.32	99.96	100.12	98.18	98.79	100.09	101.14	98.60	99.29	99.31	98.58	99.05	99.30	100.24
Si	2.522	2.577	2.613	2.626	2.638	2.436	2.305	2.438	2.498	2.554	2.511	2.614	2.519	2.521	2.541	2.476	2.542
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.464	1.425	1.395	1.375	1.371	1.544	1.500	1.549	1.489	1.429	1.468	1.390	1.486	1.473	1.481	1.470	1.444
Fe	0.033	0.017	0.010	0.014	0.012	0.023	0.017	0.021	0.036	0.060	0.039	0.014	0.016	0.042	0.014	0.049	0.037
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.459	0.386	0.353	0.337	0.315	0.539	0.492	0.549	0.467	0.383	0.455	0.362	0.446	0.425	0.395	0.466	0.432
Na	0.517	0.588	0.618	0.643	0.649	0.467	0.434	0.442	0.515	0.583	0.534	0.596	0.515	0.531	0.548	0.528	0.542
K	0.010	0.013	0.014	0.013	0.016	0.008	0.011	0.009	0.009	0.014	0.016	0.013	0.010	0.015	0.012	0.006	0.013
P	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Total	5.006	5.005	5.004	5.008	5.001	5.018	4.958	5.009	5.014	5.023	5.023	4.989	4.993	5.007	4.991	5.018	5.010
Al + Si	3.986	4.002	4.008	4.001	4.009	3.980	4.005	3.987	3.987	3.983	3.979	4.004	4.005	3.994	4.022	3.966	3.986
% An	46.6	39.1	35.8	33.9	32.1	53.2	52.5	54.9	47.1	39.1	45.3	37.3	45.9	43.8	41.4	46.6	43.8

MX-15

	1R	1I	1R	1I	1I	1R	2,0M	3,0M	4,0,0M	4,8,0M	5,0M	6G	6G	6R	6I	7,0M	8,0M
SiO ₂	46.96	47.26	46.72	47.21	47.46	49.11	46.78	49.83	45.77	48.20	45.57	46.34	46.00	47.85	46.71	45.76	49.77
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃	32.23	33.82	33.49	33.77	33.34	32.11	31.20	32.36	34.16	32.32	32.43	33.41	33.48	29.98	29.74	33.68	29.30
FeO	2.58	1.69	1.92	1.76	1.86	2.39	3.23	1.88	1.79	2.50	1.80	1.73	1.65	3.37	2.79	2.29	3.38
MgO	0.01	0.11	0.08	0.07	0.08	0.11	0.09	0.23	0.11	0.20	0.07	0.07	0.11	0.16	0.14	0.07	0.09
CaO	17.18	16.16	16.65	16.55	16.30	14.58	16.96	13.91	17.53	15.50	17.91	16.96	17.67	15.27	17.25	17.84	13.43
Na ₂ O	1.46	1.51	1.43	1.51	1.83	2.48	1.59	2.97	1.41	2.33	1.42	1.47	1.61	2.34	1.81	1.57	4.09
K ₂ O	0.15	0.05	0.05	0.03	0.05	0.13	0.18	0.12	0.04	0.13	0.02	0.06	0.05	0.25	0.22	0.05	0.27
P ₂ O ₅	0.16	0.12	0.12	0.10	0.09	0.10	0.09	0.11	0.13	0.12	0.23	0.21	0.19	0.07	0.16	0.19	0.07
Total	100.73	100.71	100.46	101.08	101.02	101.01	100.12	101.41	100.94	101.29	99.45	100.25	100.76	99.29	98.83	101.46	100.39
Si	2.168	2.160	2.148	2.158	2.167	2.240	2.181	2.252	2.102	2.201	2.130	2.136	2.118	2.242	2.208	2.099	2.301
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.753	1.822	1.815	1.816	1.795	1.725	1.714	1.723	1.850	1.739	1.786	1.814	1.816	1.656	1.656	1.822	1.577
Fe	0.099	0.064	0.073	0.067	0.071	0.091	0.124	0.070	0.067	0.095	0.070	0.066	0.062	0.130	0.109	0.087	0.130
Mg	0.000	0.006	0.005	0.004	0.005	0.006	0.005	0.014	0.006	0.013	0.004	0.004	0.006	0.011	0.008	0.004	0.005
Ca	0.849	0.792	0.820	0.809	0.797	0.711	0.847	0.674	0.863	0.757	0.896	0.837	0.872	0.766	0.874	0.876	0.665
Na	0.130	0.133	0.126	0.132	0.162	0.218	0.144	0.260	0.125	0.206	0.127	0.131	0.143	0.211	0.165	0.139	0.366
K	0.008	0.002	0.002	0.001	0.002	0.006	0.009	0.006	0.001	0.006	0.000	0.002	0.002	0.014	0.012	0.002	0.015
P	0.005	0.004	0.004	0.002	0.002	0.002	0.002	0.004	0.004	0.004	0.008	0.006	0.006	0.002	0.005	0.006	0.001
Total	5.012	4.983	4.995	4.990	5.002	5.000	5.026	5.002	5.019	5.021	5.020	4.998	5.026	5.033	5.039	5.036	5.080
Al + Si	3.921	3.982	3.963	3.974	3.962	3.965	3.895	3.975	3.952	3.940	3.916	3.950	3.934	3.898	3.864	3.921	3.878
% An	86.0	85.4	86.5	85.9	82.9	76.0	84.7	71.7	87.3	78.1	87.6	86.3	85.7	77.3	83.2	86.1	63.6

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APPENDIX E1

Clinopyroxene Notes

- 189 H 1, core large grain, A1, average of 4 in pyroxene-biotite-opaque clot, A5, small grain in contact with OPX, A6, average small grains, 10-13, core to rim of large crystal, A2, average of 14 points in large crystals, 15, edge of large crystal, A2, 16-17, core large crystal, 21, edge of same.
- 181 6-9, rim to core to rim of tabular grain, 13,14,15, independent grains.
- 201 A1, average rim around hypersthene, A4, average of 4 grains, 12-15, core and rim of small tabular grain.
- U5-185 A2, average of 13 points, 16-22, rim on hypersthene, 23-24, small grain.
- 245 1-4, rim toward core large crystal, 6-9, rimmed by amphibole, 10-14, small grains in plagioclase, A1, average of 10-14.
- U5-188 1-9, core to rim of large crystal, A(9), average of 9 points, 10, 11, separate small grains, 12, inclusion in plagioclase, A1, average of large crystal, A2, average tabular crystal.
- 236 2A, average of 4 grains, 4A, average of rim to core of crystal.
- UN 36 Core of amphibole.
- 32 Average of 4 relict grains in amphibole.
- 175 E4, relict in amphibole.
- 179 E 1A, average of 11 points in large crystal.
- 66 B B average of 3 grains, C, small inclusions in plagioclase.
- 116 3-5, rim to core of euhedral phenocryst.
- 133 1-4, core to rim of groundmass grain, 5-7, core toward rim of phenocryst, 8-10, core to rim of small phenocryst.

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189H CPX

	1	A1	A5	A6	10	11	13R	A2(14)	15	16	17	21
SiO ₂	52.14	51.82	51.76	51.35	51.79	51.96	52.60	51.91	52.78	52.13	51.90	51.84
Al ₂ O ₃	2.42	1.90	2.07	2.00	2.40	2.32	1.79	1.92	1.44	1.83	2.06	1.84
TiO ₂	0.68	0.53	0.39	0.55	0.60	0.68	0.41	0.55	0.36	0.47	0.57	0.46
Cr ₂ O ₃	0.00	0.00	0.00	0.02	0.01	0.02	0.00	0.00	0.02	0.02	0.02	0.00
FeO	7.64	7.49	7.55	8.09	7.77	7.58	7.27	7.72	7.32	7.98	8.30	7.60
MnO	0.21	0.31	0.21	0.20	0.18	0.20	0.16	0.20	0.21	0.20	0.22	0.20
MgO	14.96	15.28	15.71	14.98	14.77	14.71	15.26	15.00	15.27	14.93	14.67	14.79
CaO	22.47	21.75	22.77	22.13	22.69	23.34	23.08	22.77	22.82	22.59	22.91	22.44
Na ₂ O	0.30	0.26	0.27	0.32	0.33	0.37	0.40	0.33	0.27	0.38	0.33	0.27
Total	100.82	99.34	100.73	99.64	100.94	100.78	100.97	100.40	100.49	100.53	100.58	99.24
Si	1.913	1.927	1.893	1.905	1.908	1.890	1.921	1.910	1.940	1.918	1.894	1.933
Al ^{IV}	0.089	0.073	0.089	0.087	0.094	0.100	0.077	0.083	0.060	0.079	0.089	0.067
Ti	-	-	0.011	0.008	-	0.009	0.002	0.006	-	0.003	0.016	-
Fe ³⁺	-	-	0.007	-	-	-	-	-	-	-	0.001	-
Total Cations	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.019	0.015	-	0.008	0.017	0.009	0.010	0.009	0.010	0.010	-	0.013
Al ^{VI}	0.018	0.010	-	-	0.010	-	-	-	0.003	-	-	0.005
Cr	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.001	0.001	0.001	0.000
Fe ³⁺	0.053	0.052	0.101	0.102	0.074	0.117	0.087	0.095	0.055	0.088	0.111	0.055
Fe ²⁺	0.181	0.181	0.105	0.149	0.165	0.117	0.135	0.143	0.170	0.158	0.127	0.182
Mn	0.007	0.010	0.007	0.006	0.006	0.006	0.005	0.006	0.007	0.006	0.007	0.006
Mg	0.818	0.847	0.856	0.828	0.810	0.804	0.831	0.823	0.837	0.819	0.804	0.822
Ca	0.883	0.867	0.892	0.840	0.895	0.917	0.904	0.898	0.899	0.891	0.903	0.897
Na	0.021	0.019	0.019	0.023	0.024	0.026	0.028	0.024	0.019	0.027	0.024	0.020
Total Cations	4.000	4.000	3.998	3.997	4.000	3.996	4.000	3.998	4.000	3.999	3.992	4.000
Quad	91.283	92.692	-	-	90.584	-	-	-	94.043	-	-	93.327
Others	8.712	7.308	-	-	9.416	-	-	-	5.957	-	-	6.673
Wo	46.93	45.75	48.13	47.37	47.86	49.91	48.33	48.18	47.19	47.71	49.25	47.18
En	43.45	44.70	46.20	44.59	43.32	43.75	44.44	44.14	43.91	43.85	43.85	43.24
Fs	9.62	9.55	5.65	8.04	8.82	6.34	7.22	7.67	8.90	8.44	6.90	9.58
Ti	14.75	13.90	-	-	12.36	-	-	-	11.21	-	-	13.01
NaM2	16.77	17.58	-	-	17.53	-	-	-	21.68	-	-	19.69
Ala	68.48	68.52	-	-	70.10	-	-	-	67.10	-	-	67.30
Best name for others	CaFe ³ CaTS	CaFe ³ CaTS	-	-	CaFe ³ CaTS	-	-	-	CaFe ³ CaTS	-	-	CaFe ³ CaTS
Fe/Fe+Mg x 100	18.13	17.61	10.90	15.28	16.92	12.66	13.98	14.81	16.86	16.14	13.60	18.13

181 CPX

	6R	7C	8I	9R	13	14	15
SiO ₂	51.26	50.27	51.13	51.56	51.56	51.72	52.12
Al ₂ O ₃	2.52	2.18	2.00	0.75	0.43	0.34	0.94
TiO ₂	0.66	0.55	0.55	0.19	0.08	0.08	0.21
Cr ₂ O ₃	0.16	0.07	0.04	0.04	0.02	0.02	0.04
FeO	9.81	7.59	9.36	9.05	8.74	8.57	8.95
MnO	0.22	0.23	0.22	0.34	0.30	0.27	0.26
MgO	15.96	16.12	15.63	14.60	14.91	14.90	15.02
CaO	19.71	22.61	19.72	22.40	22.13	21.82	21.89
Na ₂ O	0.27	0.23	0.25	0.37	0.34	0.33	0.29
Total	100.57	100.25	98.90	99.50	98.51	98.05	99.72
Si	1.886	1.857	1.914	1.934	1.947	1.960	1.940
Al ^{IV}	0.109	0.095	0.086	0.033	0.019	0.015	0.041
Ti	0.005	0.015	-	0.005	0.002	0.002	0.006
Fe ³	-	0.034	-	0.028	0.032	0.023	0.012
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.013	-	0.013	-	-	-	-
Al ^{VI}	-	-	0.002	-	-	-	-
Cr	0.005	0.002	0.001	0.001	0.001	0.001	0.001
Fe ³⁺	0.103	0.075	0.070	0.031	0.011	0.016	0.049
Fe ²⁺	0.200	0.077	0.223	0.192	0.199	0.208	0.199
Mn	0.007	0.007	0.007	0.011	0.010	0.009	0.008
Mg	0.875	0.887	0.872	0.816	0.839	0.841	0.833
Ca	0.777	0.895	0.791	0.900	0.896	0.886	0.873
Na	0.019	0.016	0.013	0.027	0.025	0.024	0.021
Total Cations	3.998	3.999	4.000	4.011	4.017	4.013	4.005
Quad	-	-	91.592	-	-	-	-
Others	-	-	8.608	-	-	-	-
Wo	41.96	48.15	41.94	47.18	46.32	45.78	45.82
En	47.25	47.73	46.25	42.77	43.40	43.48	43.72
Fs	10.79	4.12	11.83	10.05	10.29	10.74	10.46
Ti	-	-	12.93	-	-	-	-
NaM2	-	-	15.16	-	-	-	-
Ala	-	-	71.91	-	-	-	-
Best name for others	-	-	CaFe ³ CaTS	-	-	-	-
Fe/Fe+Mg x 100	18.59	7.94	20.38	19.03	19.16	19.31	19.30

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201 CPX

236 CPX

	Al	A4(4)	12C	13C	14R	15R	2A	4A
SiO ₂	52.16	52.44	52.90	52.50	52.66	51.72	52.54	52.15
Al ₂ O ₃	1.04	0.92	0.79	0.96	0.83	1.10	1.09	1.17
TiO ₂	0.19	0.13	0.11	0.13	0.07	0.24	0.28	0.16
Cr ₂ O ₃	0.03	0.04	0.03	0.13	0.00	0.01	0.00	0.04
FeO	7.64	7.73	7.95	7.41	7.20	8.34	9.61	9.78
MnO	0.20	0.21	0.24	0.24	0.19	0.21	0.42	0.45
MgO	15.21	15.18	15.05	15.25	15.53	14.91	14.44	13.75
CaO	23.18	22.77	23.12	23.11	23.27	21.60	20.76	21.02
Na ₂ O	0.24	0.19	0.19	0.15	0.19	0.20	0.42	0.33
Total	99.89	99.61	100.38	99.88	99.94	98.33	99.56	98.85
Si	1.933	1.949	1.954	1.945	1.948	1.949	1.964	1.970
Al ^{IV}	0.045	0.040	0.034	0.042	0.036	0.049	0.036	0.030
Ti	0.005	0.004	0.003	0.004	0.002	0.002	-	-
Fe ³	0.017	0.007	0.009	0.009	0.014	-	-	-
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	-	-	-	-	-	0.005	0.008	0.005
Al ^{VI}	-	-	-	-	-	-	0.012	0.022
Cr	0.001	0.001	0.001	0.004	0.000	0.000	0.000	0.001
Fe ³⁺	0.045	0.046	0.038	0.040	0.036	0.055	0.039	0.022
Fe ²⁺	0.153	0.176	0.187	0.163	0.157	0.208	0.262	0.287
Mn	0.006	0.007	0.008	0.008	0.006	0.007	0.013	0.014
Mg	0.840	0.841	0.828	0.842	0.856	0.837	0.804	0.774
Ca	0.921	0.907	0.915	0.918	0.922	0.872	0.832	0.851
Na	0.017	0.014	0.014	0.011	0.014	0.015	0.030	0.024
Total Cations	4.002	3.999	4.002	4.001	4.007	3.999	4.000	4.000
Quad	-	-	-	-	-	-	96.390	96.977
Others	-	-	-	-	-	-	3.610	3.023
Wo	48.10	47.13	47.41	4.60	47.67	45.50	43.82	44.51
En	43.89	43.70	42.91	43.68	44.24	43.67	42.39	40.49
Fs	8.01	9.17	9.68	8.72	8.09	10.83	13.79	15.00
Ti	-	-	-	-	-	-	10.58	7.71
NaM2	-	-	-	-	-	-	40.91	41.00
Al4	-	-	-	-	-	-	48.51	51.29
Best name for others	-	-	-	-	-	-	ACMITE	ACMITE
Fe/Fe+Mg x 100	15.44	17.35	18.40	16.64	15.47	19.87	24.54	27.03

245 GPT

	1R	2R	3I	4I	5	7	8	9	10	11	12	13	14	Al(5)
SiO ₂	54.11	52.16	52.80	53.53	52.85	54.03	53.45	53.38	50.85	51.41	52.18	52.59	51.95	51.80
Al ₂ O ₃	0.53	0.79	0.80	0.63	0.53	0.59	0.58	0.55	1.81	1.71	1.59	2.03	1.78	1.78
TiO ₂	0.00	0.05	0.07	0.08	0.03	0.04	0.04	0.02	0.45	0.41	0.25	0.32	0.33	0.39
Cr ₂ O ₃	0.04	0.05	0.03	0.03	0.02	0.03	0.03	0.03	0.04	0.00	0.04	0.03	0.03	0.03
FeO	6.81	7.43	7.59	6.61	6.74	6.84	6.75	6.65	8.30	8.31	7.88	8.64	8.36	8.30
MnO	0.53	0.44	0.55	0.55	0.50	0.36	0.40	0.43	0.48	0.41	0.41	0.40	0.49	0.44
MgO	15.31	15.25	15.03	15.58	15.54	15.54	15.84	15.67	14.86	14.87	14.66	14.68	15.18	14.85
CaO	23.40	22.38	22.77	24.12	22.91	22.88	22.54	22.50	21.59	21.96	21.86	21.75	21.99	21.83
Na ₂ O	0.16	0.29	0.31	0.30	0.21	0.20	0.16	0.33	0.38	0.40	0.34	0.32	0.46	0.38
Total	100.89	98.84	99.95	101.43	99.53	100.31	99.79	99.56	99.47	99.48	99.21	100.76	100.79	99.80
Si	1.984	1.952	1.956	1.951	1.965	1.988	1.975	1.975	1.904	1.911	1.948	1.937	1.904	1.922
Al ^{IV}	0.016	0.035	0.035	0.027	0.023	0.012	0.025	0.024	0.080	0.075	0.052	0.063	0.077	0.078
Ti	-	0.001	0.002	0.002	0.001	-	-	0.001	0.013	0.011	-	-	0.015	-
Fe ³⁺	-	0.012	0.007	0.020	0.010	-	-	-	0.003	0.003	-	-	0.004	-
Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.000	-	-	-	-	0.001	0.001	-	-	-	0.007	0.009	-	0.011
Al ^{VI}	0.006	-	-	-	-	0.014	0.000	-	-	-	0.018	0.025	-	0.000
Cr	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.001
Fe ³⁺	0.020	0.042	0.049	0.027	0.028	0.009	0.033	0.047	0.103	0.101	0.043	0.043	0.105	0.082
Fe ²⁺	0.189	0.165	0.170	0.132	0.160	0.195	0.176	0.158	0.137	0.140	0.203	0.223	0.129	0.175
Mn	0.016	0.014	0.017	0.017	0.016	0.011	0.013	0.013	0.015	0.013	0.013	0.012	0.015	0.014
Mg	0.836	0.850	0.830	0.846	0.861	0.852	0.872	0.864	0.829	0.824	0.816	0.806	0.829	0.821
Ca	0.919	0.898	0.904	0.942	0.913	0.902	0.893	0.892	0.866	0.875	0.875	0.858	0.864	0.868
Na	0.011	0.021	0.022	0.021	0.015	0.014	0.011	0.024	0.028	0.029	0.025	0.023	0.033	0.027
Total Cations	4.000	4.004	4.001	4.007	4.004	4.000	4.000	4.000	3.991	3.995	4.000	4.000	3.989	4.000
Quartz	98.359	-	-	-	-	98.813	97.516	-	-	-	94.799	93.666	-	92.222
Others	1.641	-	-	-	-	1.187	2.484	-	-	-	5.201	6.334	-	7.778
Wo	47.28	46.92	47.49	49.06	47.19	46.28	45.99	46.60	47.27	47.57	46.20	45.48	47.42	46.56
En	43.02	44.46	43.59	44.07	44.51	43.71	44.95	45.14	45.24	44.80	43.09	42.69	45.52	44.04
Fe	9.70	8.62	8.93	6.87	8.29	10.00	9.06	8.26	7.49	7.63	10.71	11.83	7.06	9.40
Ti	0.00	-	-	-	-	4.06	2.97	-	-	-	8.39	9.32	-	9.38
NaM2	40.93	-	-	-	-	52.37	30.64	-	-	-	29.43	24.04	-	23.57
Al4	59.07	-	-	-	-	43.37	66.39	-	-	-	62.18	66.64	-	67.05
Best name for others	ACMITE	-	-	-	-	JASKITE	CaFe ³ CaTS	-	-	-	CaFe ³ CaTS	CaFe ³ CaTS	-	CaFe ³ CaTS
Fe/Fe+Mg x 100	18.41	16.24	17.00	13.49	15.70	18.62	16.78	15.47	14.20	14.56	19.90	21.71	13.43	17.59

245

188 GPI

	10	20	30	40	51	78	88	98	A(9)	10	11	12	A1(3)	A2(3)
SiO ₂	52.55	53.25	52.57	52.96	53.55	51.63	53.15	52.91	52.98	51.68	52.06	51.08	51.52	51.84
Al ₂ O ₃	0.37	0.96	0.38	0.41	0.97	0.81	0.40	0.52	0.59	0.55	0.41	1.31	0.93	0.79
TiO ₂	0.04	0.16	0.07	0.15	0.29	0.30	0.11	0.09	0.14	0.44	0.21	0.65	0.34	0.20
Cr ₂ O ₃	0.02	0.14	0.02	0.22	0.04	0.00	0.00	0.04	0.03	0.04	0.02	0.02	0.02	0.03
FeO	7.42	9.29	7.36	7.42	9.09	9.19	8.60	7.54	8.24	8.82	8.63	8.63	8.80	8.92
MnO	0.21	0.25	0.21	0.22	0.27	0.26	0.20	0.16	0.24	0.27	0.25	0.26	0.24	0.26
MgO	15.31	14.55	15.21	14.73	15.37	14.77	15.82	15.44	15.19	15.20	14.50	14.75	14.84	15.26
CaO	22.52	20.55	23.21	23.09	21.74	21.71	22.09	22.51	22.18	22.98	23.06	21.46	21.84	22.38
Na ₂ O	0.28	0.29	0.26	0.31	0.37	0.39	0.37	0.31	0.34	0.42	0.36	0.32	0.35	0.29
Total	98.72	99.44	99.29	99.51	101.69	99.06	100.74	99.52	99.93	100.40	99.50	98.48	98.88	99.97
Si	1.969	1.992	1.961	1.972	1.951	1.937	1.955	1.965	1.964	1.916	1.948	1.921	1.934	1.928
Al IV	0.016	0.008	0.017	0.018	0.042	0.036	0.017	0.023	0.026	0.024	0.018	0.058	0.041	0.035
Ti	0.001	-	0.002	0.004	0.007	0.008	0.003	0.003	0.004	0.012	0.006	0.018	0.010	0.006
Fe ³⁺	0.014	-	0.020	0.006	-	0.019	0.025	0.009	0.007	0.048	0.028	0.003	0.015	0.032
Total Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	-	0.005	-	-	0.001	-	-	-	-	-	-	-	-	-
Al VI	-	0.034	-	-	-	-	-	-	-	-	-	-	-	-
Cr	0.001	0.004	0.001	0.006	0.001	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Fe ³⁺	0.022	0.000	0.015	0.028	0.073	0.045	0.019	0.035	0.042	0.005	0.020	0.078	0.051	0.023
Fe ²⁺	0.182	0.305	0.173	0.188	0.205	0.197	0.193	0.178	0.195	0.160	0.193	0.169	0.185	0.185
Mn	0.007	0.008	0.007	0.007	0.008	0.008	0.006	0.005	0.008	0.008	0.008	0.008	0.008	0.008
Mg	0.855	0.811	0.846	0.818	0.835	0.826	0.867	0.855	0.839	0.840	0.809	0.827	0.830	0.846
Ca	0.904	0.824	0.928	0.922	0.849	0.873	0.871	0.896	0.881	0.913	0.925	0.865	0.878	0.892
Na	0.020	0.021	0.019	0.022	0.026	0.028	0.026	0.022	0.024	0.030	0.026	0.023	0.025	0.021
Total Cations	4.005	4.012	4.007	3.999	3.997	3.997	4.008	4.002	3.998	4.006	4.006	3.992	3.994	4.008
Quad	-	99.203	-	-	-	-	-	-	-	-	-	-	-	-
Others	-	0.797	-	-	-	-	-	-	-	-	-	-	-	-
Wo	46.59	42.48	47.68	47.83	44.96	46.04	45.09	46.45	45.99	47.73	48.01	46.47	46.39	46.38
En	44.04	41.82	43.45	42.43	44.20	43.56	44.90	44.31	43.80	43.90	41.98	44.42	43.84	43.98
Fe	9.37	15.70	8.87	9.74	10.84	10.39	10.01	9.23	10.20	8.37	10.02	9.11	9.77	9.63
Ti	-	13.44	-	-	-	-	-	-	-	-	-	-	-	-
NaM2	-	62.79	-	-	-	-	-	-	-	-	-	-	-	-
Al4	-	23.78	-	-	-	-	-	-	-	-	-	-	-	-
Best name for others	-	JADEITE	-	-	-	-	-	-	-	-	-	-	-	-
Fe/(Fe+Mg) x 100	17.55	27.30	16.95	18.66	19.69	19.26	18.22	17.25	18.89	16.02	19.27	17.01	18.23	17.97

ORIGINAL PAGE IS
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U5 185 CPX						32 CPX	UN36 CPX
	A2	20R	21C	22R	24C	Ave	1A
SiO ₂	51.88	51.89	51.61	52.14	53.23	50.78	52.14
Al ₂ O ₃	1.56	1.87	1.72	1.73	0.89	2.35	1.36
TiO ₂	0.49	0.41	0.50	0.53	0.38	0.52	0.36
Cr ₂ O ₃	0.00	0.01	0.00	0.00	0.00	0.02	0.00
FeO	8.80	10.63	9.17	8.46	7.42	8.48	10.51
MnO	0.41	0.39	0.41	0.50	0.33	0.36	0.36
MgO	14.92	14.79	14.74	15.06	15.56	14.52	14.37
CaO	21.02	19.38	20.70	20.79	21.55	22.09	20.60
Na ₂ O	0.38	0.32	0.25	0.54	0.39	0.35	0.15
Total	99.46	99.69	99.10	99.75	99.75	99.47	99.85
Si	1.934	1.939	1.935	1.934	1.970	1.891	1.951
Al ^{IV}	0.066	0.061	0.065	0.066	0.030	0.103	0.049
Ti	-	-	-	-	-	0.006	-
Fe ³	-	-	-	-	-	-	-
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.014	0.012	0.014	0.015	0.011	0.009	0.010
Al ^{VI}	0.003	0.021	0.011	0.009	0.009	-	0.011
Cr	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Fe ³⁺	0.063	0.040	0.043	0.066	0.028	0.116	0.028
Fe ²⁺	0.211	0.292	0.244	0.197	0.201	0.148	0.301
Mn	0.013	0.012	0.013	0.016	0.010	0.011	0.011
Mg	0.829	0.824	0.824	0.832	0.858	0.806	0.801
Ca	0.840	0.776	0.832	0.826	0.855	0.882	0.826
Na	0.027	0.023	0.018	0.039	0.028	0.025	0.011
Total Cations	4.000	4.000	4.000	4.000	4.000	3.998	4.000
Quad	93.413	93.867	93.538	93.382	96.983	-	95.112
Others	6.587	6.133	6.462	6.618	3.017	-	4.888
Wo	44.67	41.02	43.78	44.54	44.65	48.02	42.35
En	44.09	43.54	43.35	44.87	44.83	43.89	41.56
Fs	11.24	15.44	12.87	10.59	10.52	8.08	15.59
Ti	12.83	12.00	14.55	12.34	15.39	-	14.50
NaM2	25.65	24.14	18.76	32.42	40.72	-	15.57
Al ⁴	61.52	63.86	66.69	55.24	43.90	-	69.93
Best name for others	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	ACMITE	ACMITE	-	CaFe ³ CaTS
Fe/Fe+Mg x 100	20.31	26.18	22.89	19.10	19.00	15.55	27.28

ORIGINAL PAGE IS
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	116 CPX			175 CPX	179E CPX	66B CPX	
	3	4	5	E4	1A	B	C
SiO ₂	49.20	49.03	49.70	51.76	52.22	50.98	51.56
Al ₂ O ₃	2.93	3.57	2.83	1.93	1.30	2.23	1.84
TiO ₂	1.04	1.22	0.93	0.62	0.32	0.63	0.78
Cr ₂ O ₃	0.02	0.02	0.02	0.00	0.00	0.03	0.03
FeO	11.68	12.19	10.67	9.57	9.74	8.50	8.70
MnO	0.42	0.39	0.33	0.33	0.39	0.37	0.30
MgO	14.56	14.32	14.91	14.50	13.73	14.81	14.91
CaO	19.05	19.24	19.57	20.57	21.28	21.56	22.79
Na ₂ O	0.31	0.36	0.32	0.34	0.27	0.33	0.33
Total	99.21	100.34	99.28	99.62	99.25	99.44	101.24
Si	1.846	1.822	1.858	1.933	1.966	1.899	1.887
Al ^{IV}	0.130	0.156	0.125	0.067	0.034	0.098	0.079
Ti	0.024	0.021	0.017	-	-	0.003	0.021
Fe ³	-	-	-	-	-	-	0.012
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.005	0.013	0.009	0.017	0.009	0.015	-
Al ^{VI}	-	-	-	0.018	0.023	-	-
Cr	0.001	0.001	0.001	0.000	0.000	0.001	0.001
Fe ³⁺	0.165	0.178	0.146	0.038	0.012	0.095	0.090
Fe ²⁺	0.202	0.203	0.189	0.261	0.294	0.171	0.131
Mn	0.013	0.012	0.010	0.010	0.012	0.012	0.009
Mg	0.814	0.793	0.831	0.807	0.770	0.822	0.813
Ca	0.766	0.766	0.784	0.823	0.858	0.861	0.894
Na	0.023	0.026	0.023	0.025	0.020	0.024	0.023
Total Cations	3.990	3.991	3.993	4.000	4.000	3.999	3.985
Quad	-	-	-	93.317	96.573	-	-
Others	-	-	-	6.683	3.427	-	-
Wo	42.97	43.49	43.48	43.54	44.64	46.44	48.63
En	45.68	45.01	46.06	42.68	40.06	44.36	44.24
Fs	11.35	11.49	10.46	13.78	15.30	9.20	7.12
Ti	-	-	-	16.00	14.37	-	-
NaM2	-	-	-	22.62	31.26	-	-
Al4	-	-	-	61.38	54.37	-	-
Best name for others	-	-	-	CaFe ³ CaTS	JADEITE	-	-
Fe/Fe+Mg x 100	19.90	20.34	18.50	24.40	27.64	17.18	13.87

133 CPX

	1GM	2GM	4GMR	50	60	71	80	91	10R	Avg of 7
SiO ₂	52.31	53.22	52.65	52.47	52.75	53.23	52.98	53.67	52.33	52.84
Al ₂ O ₃	2.31	2.21	2.30	2.42	3.25	2.72	1.90	1.84	2.27	2.35
TiO ₂	0.66	0.59	0.55	0.57	0.52	0.68	0.41	0.55	0.64	0.57
Cr ₂ O ₃	0.00	0.00	0.00	0.01	0.33	0.00	0.00	0.00	0.00	0.01
FeO	10.61	10.10	10.01	10.50	9.98	10.93	10.04	10.06	10.54	10.31
MnO	0.30	0.29	0.34	0.34	0.36	0.31	0.30	0.30	0.39	0.32
MgO	15.09	15.12	14.95	15.30	15.14	15.34	15.05	15.01	14.45	15.04
CaO	19.26	19.29	18.60	19.10	18.60	17.24	19.43	17.98	19.18	18.74
Na ₂ O	0.25	0.21	0.23	0.29	0.32	0.28	0.29	0.19	0.23	0.25
Total	100.79	101.03	99.63	101.00	101.25	100.73	100.40	99.60	100.03	100.43
Si	1.933	1.959	1.964	1.931	1.934	1.963	1.962	2.001	1.952	1.957
Al ^{IV}	0.067	0.041	0.036	0.069	0.066	0.037	0.038	0.000	0.048	0.043
Ti	-	-	-	-	-	-	-	-	-	-
Fe ³	-	-	-	-	-	-	-	-	-	-
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.018	0.016	0.015	0.016	0.014	0.019	0.011	0.015	0.018	0.016
Al ^{VI}	0.033	0.055	0.065	0.037	0.075	0.082	0.045	0.082	0.052	0.059
Cr	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000
Fe ³⁺	0.016	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.000	0.000
Fe ²⁺	0.312	0.334	0.345	0.302	0.324	0.384	0.317	0.389	0.346	0.342
Mn	0.009	0.009	0.011	0.011	0.011	0.010	0.009	0.009	0.012	0.010
Mg	0.831	0.829	0.831	0.839	0.827	0.843	0.831	0.834	0.808	0.830
Ca	0.763	0.761	0.744	0.754	0.731	0.681	0.771	0.719	0.767	0.744
Na	0.018	0.015	0.017	0.021	0.023	0.020	0.021	0.014	0.017	0.018
Total Cations	4.000	4.019	4.027	4.000	4.015	4.039	4.005	4.063	4.014	4.019
Quad	93.254	95.875	96.384	93.148	93.425	96.339	96.180	100.139	95.179	95.659
Others	6.746	4.125	3.616	6.852	6.575	3.661	3.820	-	4.821	4.341
Wo	40.01	39.54	38.74	39.76	38.82	35.70	40.18	37.00	40.02	38.83
En	43.60	43.10	43.30	44.29	43.94	44.17	43.28	42.95	41.93	43.33
Fs	16.39	17.37	17.95	15.96	17.23	20.13	16.54	20.05	18.05	17.84
Ti	17.68	22.51	22.61	15.03	13.94	24.98	16.21	-	21.68	20.55
NaM2	17.27	20.65	24.38	19.71	22.12	26.52	29.56	-	20.09	23.24
Al4	65.05	56.84	53.00	65.26	63.33	48.49	54.23	-	58.23	56.20
Best name for others	CaAL CaTS	NaTAL	NaTAL	CaAL CaTS	CaAL CaTS	NaTAL CaTS	JADEITE		NaTAL	NaTAL
Fe/Fe+Mg x 100	27.32	28.72	29.31	26.49	28.17	31.30	27.65	31.82	30.10	29.16

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MX-15 GPF

	1	2	3	4	AL	5GM	6GM	7GM	8GM	1 GM	9 GM	AC	AR	AVG
SiO ₂	51.48	50.62	50.36	49.55	50.49	49.02	49.73	51.76	49.59	50.36	49.88	49.97	50.00	49.99
Al ₂ O ₃	4.13	4.34	4.58	4.16	4.30	5.06	5.75	2.12	5.34	3.74	3.70	4.29	3.90	4.09
TiO ₂	0.40	0.41	0.43	0.48	0.43	1.01	0.75	0.64	0.62	0.67	0.41	0.28	0.29	0.29
Cr ₂ O ₃	0.38	0.45	0.29	0.36	0.37	0.25	0.07	0.02	0.18	0.09	0.00	0.00	0.00	0.00
FeO	6.40	6.13	6.54	6.05	6.28	9.86	9.90	8.11	7.83	8.61	9.90	6.48	6.28	6.38
MnO	0.11	0.15	0.13	0.07	0.12	0.23	0.23	0.32	0.22	0.26	0.00	0.00	0.00	0.00
NaO	16.12	15.73	16.08	15.72	15.91	14.85	14.71	16.76	15.24	15.57	16.91	15.91	15.82	15.86
CaO	22.36	22.85	21.64	22.20	22.21	20.41	20.20	20.34	21.62	20.72	17.85	21.64	21.67	21.66
Na ₂ O	0.24	0.24	0.21	0.24	0.23	0.34	0.31	0.34	0.23	0.29	0.00	0.00	0.00	0.00
Total	101.62	100.72	100.26	98.83	100.34	101.03	101.65	100.41	98.87	100.31	98.65	98.57	97.96	98.27
Si	1.858	1.843	1.840	1.837	1.845	1.798	1.812	1.891	1.850	1.853	1.862	1.858	1.871	1.865
Al ^{IV}	0.142	0.157	0.160	0.163	0.155	0.202	0.188	0.091	0.147	0.147	0.138	0.142	0.129	0.135
Ti	-	-	-	-	-	-	-	0.017	0.003	-	-	-	-	-
Fe ³	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.011	0.011	0.012	0.013	0.012	0.028	0.021	0.000	0.014	0.019	0.012	0.008	0.008	0.008
Al ^{VI}	0.033	0.030	0.038	0.019	0.030	0.017	0.059	-	-	0.015	0.025	0.046	0.044	0.045
Cr	0.011	0.013	0.008	0.011	0.011	0.007	0.002	0.001	0.005	0.005	0.000	0.000	0.000	0.000
Fe ³⁺	0.093	0.108	0.105	0.124	0.108	0.146	0.108	0.132	0.134	0.114	0.090	0.080	0.069	0.074
Fe ²⁺	0.100	0.079	0.095	0.063	0.084	0.157	0.194	0.117	0.111	0.151	0.219	0.122	0.128	0.125
Na	0.003	0.005	0.004	0.002	0.004	0.007	0.007	0.010	0.007	0.008	0.000	0.000	0.000	0.000
Mg	0.867	0.854	0.876	0.868	0.866	0.812	0.799	0.913	0.847	0.854	0.941	0.882	0.882	0.882
Ca	0.865	0.884	0.848	0.882	0.870	0.802	0.789	0.796	0.864	0.817	0.714	0.862	0.869	0.866
Na	0.017	0.017	0.015	0.017	0.016	0.024	0.022	0.024	0.017	0.021	0.000	0.000	0.000	0.000
Total Cations	4.000	4.000	4.000	4.000	4.000	4.000	4.000	3.993	3.999	4.000	4.000	4.000	4.000	4.000
Quad	85.769	84.348	84.041	83.684	84.460	79.814	81.209	-	-	85.255	86.188	85.832	87.147	86.505
Others	14.231	15.652	15.959	16.316	15.541	20.186	18.791	-	-	14.745	13.812	14.168	12.853	13.495
Vo	47.21	48.67	46.60	48.63	47.77	45.31	44.27	43.62	47.41	44.84	38.11	46.21	46.24	46.23
Dn	47.33	47.00	48.16	47.88	47.59	45.85	44.83	49.98	46.48	46.86	50.21	47.25	46.95	47.07
Fe	5.46	4.33	5.24	3.49	4.64	8.84	10.90	6.41	6.11	8.31	11.68	6.54	6.81	6.69
Ti	6.39	6.08	6.34	6.91	6.44	10.97	8.92	-	-	9.93	7.69	5.24	5.97	5.69
NaM	9.88	9.16	7.99	8.90	8.88	9.52	9.51	-	-	11.08	0.00	0.00	0.00	0.00
Al4	85.73	84.74	85.67	84.19	84.68	79.50	81.57	-	-	78.99	92.31	94.76	94.03	94.31
Best name for others	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	- -	- -	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS	CaFe ³ CaTS
Fe/Fe+Mg x 100	10.35	8.43	9.81	6.79	8.88	16.16	19.56	11.36	11.61	15.06	18.87	12.16	12.67	12.45

APPENDIX E2

Orthopyroxene Notes

- 189 H A1, small grain, A1(12) average of 12 small grains, A3 enclosed in augite, A4 outside of same augite, 2-5 small granular grains.

- 181 1-5 core to rim to core of long tabular crystal, 10-12 granular grain.

- 169 H A1, large grain in contact with magnetite, A2, small grain, 3 large anhedral grains, A GM average of 4 small anhedral grains, AC1-AR1 core and rim of subhedral grain.

- 201 2-6 rim to core and rim of large euhedral crystal surrounded by augite, A2 average of 2-6, 7-8 core and rim of small granular grain, 9 smallgrain core, 10-11 core and rim of large euhedral grain, A3, average of 7-11.

- U5-185 A1, average of 11 small grains, 7-10, core and rim of typical crystal.

- 245 A2, average of 10 grains, 16-17, small crystal, 24, core large crystal.

- 236 1A, average of 3 grains, 3A, average of rim and core of small grain.

- UN 36 2A, core of amphibole.

- 175 E8, E9, average of small grains.

- 179 E 2A, average of 8 inclusions in augite, 3A, small grain on edge of augite, 4A, average of 5 tabular crystals, 32R, typical rim of larger grain.

- 66 B Average of 4 grains.

189H OPX

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	Al	Al(12)	A3	A4	2	3	4	5
SiO ₂	54.13	53.55	53.30	53.52	52.11	54.06	53.95	53.69
Al ₂ O ₃	1.20	0.94	0.99	0.84	1.02	0.90	0.97	1.12
TiO ₂	0.26	0.45	0.36	0.24	1.63	0.27	0.26	0.24
Cr ₂ O ₃	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00
FeO	17.59	18.09	18.84	18.30	18.39	18.34	17.93	18.27
MnO	0.55	0.41	0.43	0.36	0.42	0.39	0.42	0.40
MgO	26.53	26.02	25.38	25.88	25.40	26.70	26.16	25.61
CaO	1.18	0.89	0.92	0.82	0.78	0.79	0.98	0.86
Na ₂ O	0.00	0.01	0.00	0.02	0.01	0.04	0.04	0.04
Total	101.46	100.36	100.24	99.98	99.76	101.49	100.71	100.23
Si	1.937	1.942	1.943	1.950	1.904	1.938	1.948	1.953
Al ^{IV}	0.051	0.040	0.043	0.030	0.044	0.038	0.041	0.047
Ti	0.007	0.013	0.010	0.007	0.045	0.007	0.007	-
Fe ³	0.005	0.006	0.005	0.006	0.007	0.017	0.004	-
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	-	-	-	-	-	-	-	0.007
Al ^{VI}	-	-	-	-	-	-	-	0.001
Cr	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000
Fe ³⁺	0.045	0.035	0.037	0.032	0.038	0.024	0.040	0.036
Fe ²⁺	0.464	0.490	0.517	0.506	0.465	0.485	0.486	0.520
Mn	0.017	0.013	0.013	0.011	0.013	0.012	0.013	0.012
Mg	1.415	1.406	1.379	1.405	1.383	1.427	1.407	1.388
Ca	0.045	0.035	0.036	0.032	0.031	0.030	0.038	0.034
Na	0.000	0.001	0.000	0.001	0.001	0.003	0.003	0.003
Total Cations	3.994	3.993	3.993	3.999	3.973	4.034	3.993	4.000
Quad	-	-	-	-	-	-	-	95.279
Others	-	-	-	-	-	-	-	4.721
Wo	2.35	1.79	1.86	1.65	1.63	1.56	1.96	1.73
En	73.52	72.84	71.36	72.30	73.62	73.46	72.86	71.50
Fs	24.13	25.37	26.78	26.05	24.75	24.98	25.17	26.77
Ti	-	-	-	-	-	-	-	11.60
NaM2	-	-	-	-	-	-	-	4.98
Al4	-	-	-	-	-	-	-	83.42
Best name for others	-	-	-	-	-	-	-	MgFe ² CaTS
Fe/Fe+Mg x 100	24.71	25.83	27.29	26.49	25.16	25.38	25.68	27.24

181 OPK

	10	20	3R	4I	5C	10	11	12
SiO ₂	55.13	51.38	52.40	51.21	51.42	52.50	52.11	52.73
Al ₂ O ₃	0.84	0.83	0.68	0.88	1.05	0.98	1.04	1.03
TiO ₂	0.28	0.29	0.16	0.39	0.35	0.31	0.29	0.23
Cr ₂ O ₃	0.02	0.04	0.02	0.05	0.05	0.04	0.00	0.05
FeO	21.75	21.68	22.90	21.22	21.11	21.12	21.33	21.13
MnO	0.54	0.52	0.61	0.46	0.44	0.46	0.43	0.47
MgO	22.59	22.66	21.49	23.13	23.25	23.38	23.30	24.28
CaO	1.30	1.23	0.86	1.39	1.66	1.54	1.57	1.38
Na ₂ O	0.00	0.00	1.96	0.00	0.01	0.00	0.00	0.01
Total	100.50	98.63	101.08	98.75	99.34	100.33	100.29	101.33
Si	1.967	1.936	1.920	1.923	1.918	1.933	1.923	1.923
Al ^{IV}	0.033	0.037	0.029	0.039	0.046	0.043	0.043	0.044
Ti	-	0.008	0.004	0.011	0.010	0.009	0.008	0.007
Fe ³	-	0.019	0.047	0.027	0.026	0.016	0.022	0.025
Tot Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.008	-	-	-	-	-	-	-
Al ^{VI}	0.003	-	-	-	-	-	-	-
Cr	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001
Fe ³⁺	0.014	0.017	0.121	0.010	0.019	0.025	0.023	0.019
Fe ²⁺	0.660	0.621	0.483	0.591	0.378	0.584	0.584	0.569
Mn	0.017	0.017	0.019	0.013	0.014	0.014	0.014	0.015
Mg	1.246	1.273	1.173	1.296	1.293	1.294	1.294	1.320
Ca	0.052	0.050	0.034	0.056	0.066	0.061	0.062	0.054
Na	0.000	0.000	0.139	0.000	0.001	0.000	0.000	0.001
Total Cations	4.000	4.012	4.032	4.012	4.013	4.000	4.004	4.008
Quad	96.678	-	-	-	-	-	-	-
Others	3.322	-	-	-	-	-	-	-
Wo	2.63	2.56	2.00	2.38	3.43	3.13	3.20	2.78
En	63.66	63.49	69.43	66.68	66.75	66.74	66.70	67.95
Fs	33.70	31.95	28.57	30.44	29.83	30.13	30.10	29.27
Ti	19.01	-	-	-	-	-	-	-
NaM2	0.00	-	-	-	-	-	-	-
Ala	80.99	-	-	-	-	-	-	-
Best name for others	Mg TAl	-	-	-	-	-	-	-
Fe/Fe+Mg x 100	34.62	32.79	29.13	31.34	30.39	31.10	31.09	30.11

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	169H OPX						175 OPX
	Al	A2	3	A GM	AO-1	AR-1	ES, 9
SiO ₂	54.08	53.63	53.64	52.30	52.38	52.54	51.47
Al ₂ O ₃	0.85	0.82	0.98	0.82	0.76	0.66	1.12
TiO ₃	0.08	0.10	3.10	0.16	0.19	0.13	0.50
Cr ₂ O ₃	0.00	0.00	0.02	0.01	0.01	0.03	0.00
FeO	20.71	20.62	20.08	21.13	21.08	21.36	21.17
MnO	0.87	0.85	0.82	0.84	0.80	0.96	0.61
MgO	23.73	23.63	23.54	24.18	23.78	23.33	22.95
CaO	0.56	0.56	0.55	0.64	0.66	0.69	1.42
Na ₂ O	0.01	0.00	0.00	0.01	0.09	0.01	0.02
Total	100.89	100.21	99.73	100.09	99.75	99.71	99.26
Si	1.981	1.978	1.985	1.933	1.942	1.955	1.922
Al ^{IV}	0.019	0.022	0.015	0.036	0.033	0.029	0.049
Ti	-	-	-	0.004	0.005	0.004	0.014
Fe ³	-	-	-	0.027	0.019	0.012	0.015
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.002	0.003	0.003	-	-	-	-
Al ^{VI}	0.018	0.014	0.027	-	-	-	-
Cr	0.000	0.000	0.001	0.000	0.000	0.001	0.000
Fe ³⁺	0.000	0.003	0.000	0.009	0.020	0.017	0.036
Fe ²⁺	0.636	0.633	0.635	0.586	0.590	0.619	0.581
Mn	0.027	0.027	0.026	0.026	0.025	0.030	0.019
Mg	1.296	1.299	1.298	1.332	1.314	1.294	1.277
Ca	0.022	0.022	0.022	0.025	0.026	0.028	0.057
Na	0.001	0.000	0.000	0.001	0.006	0.001	0.001
Total Cations	4.002	4.000	4.011	4.010	4.005	4.005	3.990
Quad	98.107	97.798	98.468	-	-	-	-
Others	1.893	2.202	1.332	-	-	-	-
Wo	1.13	1.13	1.12	1.30	1.36	1.42	2.97
En	66.30	66.46	66.40	68.34	68.08	66.66	66.68
Fs	32.57	32.40	32.49	30.15	30.56	31.92	30.35
Ti	10.09	11.19	15.37	-	-	-	-
NaM2	3.25	0.00	0.00	-	-	-	-
Al4	86.66	88.31	84.63	-	-	-	-
Best name for others	MgAl CaTS	MgAl CaTS	MgAl CaTS	-	-	-	-
Fe/Fe+Mg x 100	32.34	32.77	32.35	30.35	30.98	32.38	31.28

201 OFI

	2R	3I	4I	5C	6R	42	7C	8R	9C	10C	11R	13(5)
SiO ₂	51.77	52.38	51.77	50.59	52.26	51.75	52.83	52.7a	52.14	52.49	52.86	52.61
Al ₂ O ₃	1.22	1.47	1.31	1.66	0.78	1.29	1.05	0.90	0.86	0.99	0.89	0.93
TiO ₂	0.59	0.22	0.29	1.55	0.20	0.37	0.29	0.25	0.26	0.19	0.29	0.25
Cr ₂ O ₃	0.02	0.04	0.02	0.02	0.04	0.02	0.00	0.00	0.00	0.01	0.02	0.00
FeO	20.55	19.76	19.7a	19.16	19.88	19.81	20.48	20.00	22.39	20.45	19.99	20.66
MnO	0.45	0.37	0.40	0.36	0.46	0.40	0.52	0.47	0.44	0.52	0.49	0.49
MgO	24.02	23.16	23.91	23.09	23.94	23.65	23.70	24.10	24.15	23.88	23.66	23.90
CaO	0.91	1.52	2.78	2.99	0.87	1.81	1.51	1.01	1.11	1.79	1.38	1.36
Na ₂ O	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.33	99.12	100.22	99.43	98.43	99.30	100.38	99.47	101.35	100.32	99.58	100.20
Si	1.917	1.947	1.905	1.872	1.954	1.918	1.942	1.950	1.921	1.932	1.956	1.938
Al ^{IV}	0.053	0.053	0.057	0.072	0.034	0.056	0.045	0.039	0.037	0.043	0.039	0.040
Ti	0.016	-	0.008	0.043	0.006	0.016	0.008	0.007	0.007	0.005	0.005	0.007
Fe ³	0.014	-	0.030	0.013	0.006	0.009	0.005	0.003	0.035	0.020	-	0.014
Tot Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	-	0.006	-	-	-	-	-	-	-	-	0.003	-
Al ^{VI}	-	0.012	-	-	-	-	-	-	-	-	-	-
Cr	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.001	0.000
Fe ³⁺	0.039	0.027	0.026	0.060	0.027	0.047	0.040	0.036	0.002	0.038	0.037	0.026
Fe ²⁺	0.553	0.587	0.513	0.465	0.577	0.533	0.571	0.569	0.598	0.562	0.583	0.575
Mn	0.014	0.012	0.012	0.011	0.015	0.013	0.016	0.015	0.014	0.016	0.015	0.015
Mg	1.325	1.294	1.311	1.273	1.334	1.307	1.298	1.328	1.319	1.310	1.305	1.312
Ca	0.036	0.061	0.110	0.119	0.035	0.072	0.059	0.040	0.044	0.071	0.055	0.054
Na	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Cations	3.999	4.000	4.020	3.976	3.999	3.993	3.994	3.993	4.014	4.004	3.998	4.002
Quad	-	94.734	-	-	-	-	-	-	-	-	-	-
Others	-	5.266	-	-	-	-	-	-	-	-	-	-
Vo	1.89	3.12	5.67	6.39	1.79	3.76	3.08	2.07	2.22	3.63	2.82	2.77
En	69.21	68.65	67.80	68.58	68.56	68.34	67.30	68.56	67.29	67.43	67.19	67.61
Fe	28.90	30.23	26.53	25.03	29.65	27.89	29.61	29.37	30.49	28.93	29.99	29.62
Ti	-	10.46	-	-	-	-	-	-	-	-	-	-
NaH2	-	0.00	-	-	-	-	-	-	-	-	-	-
Al4	-	89.34	-	-	-	-	-	-	-	-	-	-
Rest name for others	-	NaFe ² CATE	-	-	-	-	-	-	-	-	-	-
Fe/Fe+Mg x 100	29.46	31.20	28.12	26.74	30.19	28.98	30.55	29.99	31.18	30.02	30.86	30.47

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	179E OPX				236 OPX		UN36 OPX
	2A	3A	4A	32R	1A	3A	2A
SiO ₂	52.57	51.53	52.17	51.81	53.16	52.84	52.15
Al ₂ O ₃	0.88	0.77	0.81	0.53	1.07	1.11	1.20
TiO ₂	0.36	0.26	0.28	0.32	0.20	0.36	0.35
Cr ₂ O ₃	0.00	0.03	0.00	0.00	0.03	0.02	0.01
FeO	24.49	26.39	26.07	27.26	22.45	21.95	20.45
MnO	0.77	0.87	0.88	0.97	0.94	0.74	0.51
MgO	20.69	19.81	19.48	18.66	21.89	22.04	23.59
CaO	1.26	0.97	1.17	0.88	1.32	1.61	1.65
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	101.02	100.63	100.86	100.43	101.06	100.67	99.91
Si	1.962	1.945	1.966	1.972	1.965	1.957	1.927
Al ^{IV}	0.038	0.034	0.034	0.024	0.035	0.043	0.052
Ti	-	0.007	-	0.005	-	-	0.010
Fe ³	-	0.013	-	-	-	-	0.011
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	0.010	-	0.008	0.005	0.006	0.010	-
Al ^{VI}	0.000	-	0.002	-	0.012	0.006	-
Cr	0.000	0.001	0.000	0.000	0.001	0.001	0.000
Fe ³⁺	0.018	0.020	0.017	0.019	0.011	0.017	0.041
Fe ²⁺	0.746	0.780	0.804	0.849	0.683	0.663	0.359
Mn	0.024	0.028	0.028	0.031	0.029	0.023	0.016
Mg	1.151	1.115	1.094	1.058	1.206	1.217	1.299
Ca	0.050	0.039	0.047	0.036	0.052	0.064	0.065
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total Cations	4.000	4.002	4.000	3.998	4.000	4.000	4.000
Quad	96.160	-	96.552	-	96.514	95.718	-
Others	3.840	-	3.448	-	3.486	4.282	-
Wo	2.59	2.03	2.43	1.85	2.69	3.29	3.40
En	59.08	57.65	56.22	54.47	62.12	62.58	67.54
Fs	38.33	40.32	41.35	43.69	35.18	34.13	29.06
Ti	20.83	-	18.71	-	13.76	18.98	-
NaM2	0.00	-	0.00	-	0.00	0.00	-
Al4	79.17	-	81.29	-	86.24	81.02	-
Best names for others	Mg TA1	- -	Mg TA1	- -	MgAl CaTS	Mg TA1	- -
Fe/Fe+Mg x 100	39.35	41.16	42.38	44.51	36.16	35.29	30.08

	245 OPX				U5-185 OPX			66B OPX
	A2(10)	16	17	24	Al	7C	10R	A
SiO ₂	52.88	52.54	53.84	53.54	53.19	53.17	53.34	52.64
Al ₂ O ₃	1.14	1.18	0.79	1.09	1.13	1.18	1.04	1.04
TiO ₂	0.26	0.26	0.19	0.30	0.31	0.34	0.27	0.42
Cr ₂ O ₃	0.02	0.07	0.00	0.20	0.04	0.03	0.05	0.01
FeO	20.22	20.22	20.29	20.65	19.08	19.44	18.79	18.36
MnO	0.74	0.70	0.91	0.61	0.75	0.67	0.80	0.56
MgO	23.86	24.00	24.34	23.66	23.94	23.71	24.04	24.91
CaO	1.54	1.77	0.81	1.20	1.60	1.64	1.65	1.40
Na ₂ O	0.00	0.01	0.23	0.00	0.00	0.02	0.00	0.02
Total	100.66	100.75	101.40	101.25	100.04	100.20	99.98	99.36
Si	1.937	1.924	1.954	1.958	1.956	1.955	1.961	1.936
Al ^{IV}	0.049	0.051	0.034	0.042	0.044	0.045	0.039	0.045
Ti	0.007	0.007	0.005	-	-	-	-	0.012
Fe ³	0.007	0.018	0.007	-	-	-	-	0.007
Tet Total	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ti	-	-	-	0.008	0.009	0.009	0.007	-
Al ^{VI}	-	-	-	0.005	0.005	0.006	0.006	-
Cr	0.001	0.002	0.000	0.001	0.001	0.001	0.001	0.000
Fe ³⁺	0.042	0.032	0.043	0.021	0.021	0.021	0.016	0.029
Fe ²⁺	0.557	0.545	0.554	0.611	0.566	0.577	0.561	0.500
Mn	0.023	0.022	0.028	0.019	0.023	0.021	0.025	0.017
Mg	1.303	1.310	1.316	1.289	1.312	1.299	1.317	1.366
Ca	0.060	0.069	0.032	0.047	0.063	0.065	0.065	0.055
Na	0.000	0.001	0.016	0.000	0.000	0.001	0.000	0.001
Total Cations	3.996	4.000	3.998	4.000	4.000	4.000	4.000	3.994
Quad	-	-	-	95.757	95.600	95.480	96.108	-
Others	-	-	-	4.243	4.400	4.520	3.892	-
Wo	3.15	3.61	1.66	2.42	3.25	3.33	3.34	2.87
En	67.83	68.08	69.23	66.22	67.59	66.95	67.77	71.10
Fs	29.02	28.31	29.11	31.37	29.16	29.72	28.89	26.03
Ti	-	-	-	16.28	16.31	16.78	16.10	-
NaM2	-	-	-	0.00	0.00	2.54	0.00	-
Al ⁴	-	-	-	83.72	83.69	80.67	83.90	-
Best name for others	-	-	-	MgFe ² Cats	MgFe ² Cats	MgFe ² Cats	MgFe ² Cats	-
Fe/Fe+Mg x 100	29.96	29.37	29.60	32.14	30.14	30.75	29.88	26.80

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APPENDIX F

Amphibole compositions, Captains Bay Pluton

169 K

	1	2	3	4	5	6	7
SiO ₂	49.90	51.24	49.51	49.27	49.68	49.84	49.84
TiO ₂	0.99	0.86	1.50	1.47	1.46	1.35	1.43
Al ₂ O ₃	6.14	5.63	6.66	6.69	6.78	6.52	6.69
Cr ₂ O ₃	0.04	0.02	0.03	0.04	0.03	0.03	0.00
FeO	11.90	11.86	12.23	12.24	12.17	12.05	11.93
MnO	0.33	0.34	0.27	0.30	0.27	0.27	0.20
MgO	15.91	16.44	15.42	15.41	15.43	15.52	15.38
CaO	11.01	11.10	11.04	11.10	11.43	11.57	11.32
Na ₂ O	0.82	0.73	0.88	0.85	0.93	0.84	0.92
K ₂ O	0.29	0.33	0.55	0.51	0.48	0.49	0.57
P ₂ O ₅	0.13	0.14	0.12	0.13	0.14	0.04	0.06
Total	97.46	98.69	98.64	98.02	98.80	98.52	98.33
Si	6.891	6.976	6.791	6.795	6.796	6.838	6.843
Al ^{IV}	0.761	0.676	0.861	0.857	0.856	0.814	0.809
Tet.Total	7.652	7.652	7.652	7.652	7.652	7.652	7.652
Al ^{VI}	0.236	0.227	0.214	0.227	0.236	0.237	0.271
Ti	0.101	0.083	0.153	0.149	0.148	0.137	0.145
Cr	0.004	0.000	0.000	0.004	0.000	0.000	0.000
Fe	1.374	1.350	1.401	1.408	1.389	1.381	1.366
Mn	0.036	0.036	0.028	0.032	0.028	0.028	0.020
Mg	3.275	3.336	3.152	3.168	3.143	3.173	3.147
Ca	1.629	1.618	1.687	1.639	1.674	1.699	1.664
Na	0.219	0.191	0.229	0.227	0.245	0.221	0.242
K	0.048	0.056	0.092	0.089	0.084	0.084	0.097
P	0.012	0.016	0.012	0.012	0.016	0.004	0.004
Total	14.587	14.565	14.619	14.607	14.614	14.616	14.607
Fe/Fe+Mg	.295	.288	.308	.308	.306	.303	.303

Note: 1. 2 small grains in a biotite and opaque aggregate; 3-7 poikilitic grain enclosing plagioclase, orthopyroxene and opaques.

U5-185

	1	2	3	5	6
SiO ₂	55.21	53.77	54.63	55.66	55.02
TiO ₂	0.39	0.41	0.43	0.29	0.18
Al ₂ O ₃	2.21	1.91	2.13	2.62	1.81
Cr ₂ O ₃	0.07	0.00	0.05	0.01	0.02
FeO	7.08	7.20	7.39	8.02	7.28
MnO	0.40	0.33	0.31	0.38	0.37
MgO	20.13	20.00	20.35	19.96	20.61
CaO	11.85	11.49	11.34	11.82	11.31
Na ₂ O	0.44	0.47	0.47	0.44	0.47
K ₂ O	0.12	0.08	0.16	0.18	0.11
P ₂ O ₅	0.11	0.07	0.02	0.04	0.04
Total	98.01	95.74	97.29	99.42	97.22
Si	7.374	7.365	7.363	7.350	7.408
Al IV	0.278	0.278	0.289	0.302	0.244
Tet.Total	7.652	7.652	7.652	7.652	7.652
Al VI	0.067	0.018	0.047	0.105	0.040
Ti	0.037	0.040	0.039	0.027	0.016
Cr	0.004	0.000	0.004	0.000	0.000
Fe	0.785	0.824	0.830	0.883	0.818
Mn	0.044	0.036	0.035	0.039	0.039
Mg	4.004	4.081	4.085	3.925	4.137
Ca	1.691	1.685	1.637	1.670	1.627
Na	0.114	0.121	0.118	0.108	0.118
K	0.018	0.012	0.027	0.027	0.016
P	0.011	0.008	0.000	0.003	0.004
Total	14.426	14.476	14.475	14.439	14.467
Fe/Fe+Mg	.164	.168	.169	.184	.165

Note: 1, 5, 6 rim on orthopyroxene.

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179 E

	1	2	3	4	5	6
SiO ₂	49.43	48.64	49.00	49.92	50.00	48.80
TiO ₂	0.79	0.85	0.50	0.57	0.64	0.78
Al ₂ O ₃	4.96	5.99	3.56	5.53	4.47	5.57
Cr ₂ O ₃	0.04	0.01	0.03	0.03	0.03	0.04
FeO	14.67	15.88	13.70	15.70	15.10	15.40
MnO	0.38	0.35	0.44	0.44	0.42	0.39
MgO	13.96	13.23	14.49	14.25	14.67	13.53
CaO	11.08	11.08	14.31	11.18	10.71	10.82
Na ₂ O	1.00	1.11	1.05	1.09	0.90	1.04
K ₂ O	0.37	0.49	0.30	0.47	0.36	0.54
P ₂ O ₅	0.00	0.01	0.09	0.11	0.10	0.12
Total	96.68	97.64	97.46	99.30	97.39	97.03
Si	6.996	6.872	6.953	6.913	7.029	6.907
Al ^{IV}	0.656	0.780	0.591	0.739	0.623	0.745
Tet.Total	7.652	7.652	7.544	7.652	7.652	7.652
Al ^{VI}	0.169	0.214	0.000	0.163	0.115	0.181
Ti	0.081	0.084	0.050	0.057	0.066	0.083
Cr	0.004	0.000	0.000	0.000	0.000	0.004
Fe	1.738	1.874	1.624	1.816	1.773	1.819
Mn	0.040	0.040	0.050	0.048	0.049	0.045
Mg	2.945	2.780	3.064	2.938	3.073	2.853
Ca	1.680	1.676	2.173	1.658	1.613	1.640
Na	0.275	0.304	0.287	0.292	0.243	0.282
K	0.062	0.084	0.054	0.081	0.062	0.095
F	0.000	0.000	0.000	0.012	0.008	0.012
Total	14.646	14.708	14.852	14.718	14.655	14.667
Fe/Fe+Mg	.371	.403	.346	.382	.366	.389

Note: 1. 3 rim on clinopyroxenes; 2 rim on orthopyroxene.

	1	2	3	4	5	6
SiO ₂	48.93	49.46	48.59	50.78	50.39	50.82
TiO ₂	1.04	0.81	1.16	0.65	0.81	0.81
Al ₂ O ₃	4.82	4.56	5.05	3.62	4.63	5.28
Cr ₂ O ₃	0.02	0.04	0.04	0.04	0.05	0.02
FeO	12.09	12.04	12.68	11.18	11.73	12.70
MnO	0.27	0.32	0.21	0.37	0.28	0.39
MgO	16.58	16.38	16.08	16.96	16.25	16.43
CaO	11.14	10.89	11.12	10.91	11.21	11.23
Na ₂ O	1.12	1.13	1.22	0.74	0.97	1.11
K ₂ O	0.33	0.36	0.42	0.29	0.44	0.39
P ₂ O ₅	0.05	0.06	0.05	0.18	0.19	0.12
Total	96.39	96.21	96.64	95.72	96.94	99.29
Si	6.883	6.961	6.843	7.118	7.004	6.931
Al ^{IV}	0.769	0.691	0.809	0.534	0.648	0.721
Tet.Total	7.652	7.652	7.652	7.652	7.652	7.652
Al ^{VI}	0.028	0.065	0.025	0.064	0.107	0.122
Ti	0.107	0.083	0.120	0.066	0.081	0.077
Cr	0.000	0.004	0.004	0.004	0.004	0.000
Fe	1.420	1.417	1.492	1.305	1.364	1.448
Mn	0.029	0.037	0.021	0.040	0.033	0.044
Mg	3.477	3.437	3.376	3.542	3.363	3.337
Ca	1.676	1.640	1.677	1.635	1.668	1.635
Na	0.305	0.306	0.331	0.198	0.260	0.293
K	0.058	0.062	0.074	0.048	0.077	0.062
P	0.004	0.004	0.004	0.018	0.018	0.011
Total	14.755	14.706	14.775	14.573	14.624	14.694
Fe/Fe+Mg	.290	.292	.306	.269	.288	.303

	1W	1W	10	1,0M	2W	2W	2I	2I	2I	2C	2C	2C	2,0M	5,0M	4,0M
SiO_2	52.437	49.392	46.058	55.417	52.670	53.414	50.895	51.673	51.598	51.888	53.184	52.599	51.555	53.571	53.955
TiO_2	0.118	0.116	0.078	0.102	0.103	0.130	0.103	0.108	0.133	0.107	0.095	0.103	0.098	0.125	0.099
Al_2O_3	30.834	32.609	32.988	28.039	30.337	29.516	29.433	29.261	29.956	28.874	29.384	28.846	29.093	28.587	29.009
FeO	0.820	0.759	0.714	0.699	0.742	1.265	0.755	0.733	0.765	0.731	0.717	0.811	0.760	0.774	0.755
MnO	0.004	0.004	-	0.031	0.021	0.008	0.014	0.000	0.003	0.016	0.007	0.005	0.011	0.004	0.025
MgO	0.155	0.126	0.140	0.105	0.143	0.346	0.136	0.140	0.149	0.149	0.159	0.273	0.153	0.144	0.122
CaO	12.643	13.171	16.860	11.262	11.897	11.818	12.128	11.763	11.782	11.462	11.259	10.906	11.330	11.750	11.174
Na_2O	4.277	3.694	1.682	4.791	4.879	4.963	4.408	5.139	5.605	5.346	5.628	5.235	5.470	5.372	5.660
K_2O	0.364	0.286	0.064	0.417	0.405	0.394	0.372	0.429	0.398	0.431	0.458	0.472	0.392	0.341	0.375
Total	101.657	100.162	98.587	100.867	101.201	101.859	98.249	99.249	100.393	99.008	100.894	99.255	98.865	100.671	101.158
Si	2.351	2.253	2.198	2.486	2.370	2.393	2.362	2.376	2.351	2.391	2.402	2.411	2.380	2.424	2.426
Ti	0.004	0.004	0.002	0.003	0.003	0.004	0.003	0.003	0.004	0.003	0.003	0.003	0.003	0.004	0.003
Al	1.629	1.753	1.783	1.482	1.609	1.558	1.610	1.586	1.609	1.568	1.564	1.558	1.583	1.524	1.538
Fe	0.030	0.028	0.028	0.026	0.027	0.047	0.029	0.028	0.029	0.028	0.027	0.031	0.029	0.029	0.028
Mn	0.000	0.000	-	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.010	0.008	0.009	0.007	0.009	0.023	0.009	0.009	0.010	0.010	0.010	0.018	0.010	0.009	0.008
Ca	0.607	0.643	0.862	0.541	0.573	0.567	0.603	0.573	0.575	0.566	0.544	0.535	0.560	0.569	0.538
Na	0.371	0.326	0.155	0.416	0.425	0.431	0.396	0.458	0.495	0.477	0.492	0.465	0.489	0.471	0.493
K	0.020	0.016	0.003	0.023	0.023	0.022	0.022	0.025	0.023	0.025	0.026	0.027	0.023	0.019	0.021
Total	5.026	5.036	5.046	4.989	5.045	5.049	5.038	5.068	5.098	5.072	5.072	5.052	5.080	5.054	5.059
Al + Si	3.980	4.006	3.981	3.968	3.979	3.951	3.972	3.962	3.960	3.959	3.966	3.969	3.963	3.948	3.964
X An	60.8	65.3	84.5	55.2	56.1	55.6	59.1	54.5	52.6	53.0	51.2	52.1	52.2	53.7	51.1

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	1	2	3	4
SiO ₂	50.27	50.85	50.30	48.62
TiO ₂	0.68	0.66	0.64	0.68
Al ₂ O ₃	5.50	5.32	5.32	5.43
Cr ₂ O ₃	0.01	0.05	0.00	0.00
FeO	13.48	13.03	13.06	13.64
MnO	0.41	0.45	0.47	0.44
MgO	15.81	15.70	16.04	15.84
CaO	11.09	11.41	11.08	11.10
Na ₂ O	1.18	1.32	1.06	1.32
K ₂ O	0.50	0.38	0.43	0.46
P ₂ O ₅	0.18	0.20	0.12	0.24
Total	99.10	99.36	98.52	97.77
Si	6.896	6.946	6.930	6.803
Al ^{IV}	0.756	0.706	0.722	0.849
Tot. Total	7.652	7.652	7.652	7.652
Al ^{VI}	0.129	0.148	0.139	0.046
Ti	0.068	0.064	0.064	0.069
Cr	0.000	0.004	0.006	0.000
Fe	1.545	1.487	1.504	1.593
Mn	0.044	0.048	0.052	0.049
Mg	3.232	3.194	3.295	3.301
Ca	1.630	1.667	1.633	1.663
Na	0.310	0.349	0.283	0.357
K	0.084	0.064	0.073	0.078
P	0.020	0.020	0.012	0.024
Total	14.715	14.696	14.707	14.832
Fe/Fe+Mg	.323	.318	.313	.325

Note: 1-4 replaces orthopyroxene.

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	1	2	3	4	5	6	7	8
SiO ₂	50.02	53.19	53.23	51.05	51.04	52.34	50.66	52.13
TiO ₂	0.33	0.13	0.23	0.22	0.23	0.16	0.13	0.10
Al ₂ O ₃	4.01	1.32	1.25	1.23	3.64	2.14	4.70	2.15
Cr ₂ O ₃	0.02	0.04	0.03	0.00	0.02	0.01	0.02	0.00
FeO	16.05	14.60	14.24	13.09	14.04	14.28	12.48	12.04
MnO	0.34	0.41	0.40	0.41	0.23	0.46	0.29	0.28
MgO	13.20	15.89	15.15	16.12	14.88	15.23	15.85	16.78
CaO	12.35	12.06	12.31	11.57	12.57	12.58	12.04	11.89
Na ₂ O	0.22	0.08	0.10	0.13	0.27	0.14	0.25	0.24
K ₂ O	0.13	0.05	0.05	0.03	0.11	0.10	0.42	0.05
P ₂ O ₅	0.00	0.00	0.09	0.01	0.02	0.05	0.00	0.00
Total	96.67	97.76	97.09	95.85	97.04	97.48	96.85	95.66
Si	7.116	7.392	7.442	7.457	7.162	7.303	7.072	7.328
Al IV	0.536	0.216	0.205	0.195	0.490	0.348	0.580	0.324
Tet. Total	7.652	7.608	7.647	7.652	7.652	7.651	7.652	7.652
Al VI	0.136	0.000	0.000	0.007	0.111	0.000	0.190	0.030
Ti	0.033	0.012	0.240	0.021	0.024	0.016	0.012	0.008
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	1.907	1.697	1.662	1.538	1.647	1.663	1.455	1.415
Mn	0.037	0.044	0.045	0.045	0.024	0.053	0.033	0.033
Mg	2.796	3.292	3.155	3.374	3.109	3.166	3.298	3.515
Ca	1.882	1.794	1.842	1.740	1.886	1.880	1.799	1.791
Na	0.058	0.020	0.024	0.033	0.070	0.037	0.065	0.066
K	0.021	0.008	0.008	0.004	0.016	0.016	0.074	0.008
P	0.000	0.000	0.008	0.000	0.000	0.004	0.000	0.000
Total	14.523	14.475	14.415	14.413	14.539	14.486	14.578	14.517
Fe/Fe+Mg	.405	.340	.345	.313	.346	.344	.306	.287

32B-GR

	1	2	3	4	5	6
SiO ₂	52.59	49.57	50.75	52.64	50.85	53.08
TiO ₂	0.64	1.33	0.77	0.40	1.16	0.35
Al ₂ O ₃	3.07	4.62	3.82	2.39	4.71	3.08
Cr ₂ O ₃	0.04	0.00	0.00	0.00	0.00	0.01
FeO	11.11	12.43	10.65	9.42	12.43	11.19
MnO	0.29	0.30	0.32	0.27	0.42	0.26
MgO	17.09	15.57	16.70	18.38	15.66	17.29
CaO	11.84	11.80	12.00	11.81	11.58	11.93
Na ₂ O	0.80	1.17	0.95	0.66	1.41	0.79
K ₂ O	0.22	0.33	0.27	0.12	0.34	0.18
P ₂ O ₅	0.04	0.07	0.06	0.09	0.16	0.06
Total	97.73	97.20	96.29	96.17	98.72	98.21
Si	7.214	6.932	7.079	7.276	6.981	7.234
Al ^{IV}	0.438	0.720	0.573	0.376	0.671	0.418
Tec.Total	7.652	7.652	7.652	7.652	7.652	7.652
Al ^{VI}	0.057	0.039	0.053	0.009	0.090	0.074
Ti	0.064	0.139	0.078	0.041	0.117	0.036
Cr	0.004	0.000	0.000	0.000	0.000	0.000
Fe	1.272	1.453	1.240	1.087	1.426	1.271
Mn	0.032	0.033	0.037	0.028	0.048	0.028
Mg	3.494	3.242	3.472	3.784	3.203	3.511
Ca	1.739	1.765	1.793	1.748	1.700	1.739
Na	0.209	0.316	0.253	0.174	0.375	0.208
K	0.036	0.057	0.045	0.020	0.056	0.028
P	0.004	0.008	0.004	0.008	0.016	0.004
Total	14.563	14.704	14.627	14.532	14.683	14.551
Fe/Fe+Mg	.267	.309	.263	.223	.308	.266

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO ₂	49.62	52.23	43.76	43.95	43.57	49.64	51.12	50.59	51.19	52.13	51.90	49.82	51.34
TiO ₂	0.78	0.60	1.53	1.63	1.51	1.13	0.34	0.83	0.28	0.51	0.84	0.87	0.68
Al ₂ O ₃	5.21	4.34	9.79	9.93	5.37	5.13	4.46	4.44	4.25	4.63	4.08	4.68	3.87
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.03	0.03	0.03	0.03	0.02
FeO	11.12	11.09	12.88	12.94	10.74	10.89	11.13	10.80	10.12	11.25	10.43	10.82	10.29
MnO	0.55	0.62	0.31	0.33	0.40	0.50	0.61	0.59	0.88	0.57	0.46	0.44	0.57
MgO	16.68	18.12	14.27	14.42	15.71	16.93	17.14	17.75	18.82	18.05	17.90	16.57	17.76
CaO	11.32	10.79	11.14	10.99	10.21	10.96	10.91	11.09	10.99	11.09	11.52	11.33	11.49
Na ₂ O	1.28	0.91	2.06	1.74	0.84	1.14	0.68	0.80	0.30	0.80	0.76	1.09	0.75
K ₂ O	0.39	0.22	0.54	0.62	0.09	0.28	0.27	0.38	0.29	0.25	0.38	0.33	0.26
Total	96.95	98.91	96.23	96.54	94.47	96.61	96.66	97.28	97.14	99.31	98.30	95.97	97.04
Si	6.911	7.073	6.258	6.257	6.508	6.922	7.033	6.990	7.043	7.042	7.069	6.991	7.086
Al ^{IV}	0.741	0.571	1.494	1.495	0.942	0.730	0.559	0.662	0.605	0.610	0.583	0.661	0.566
Total	7.652	7.652	7.652	7.652	7.450	7.652	7.652	7.652	7.652	7.652	7.652	7.652	7.652
Al ^{VI}	0.113	0.112	0.255	0.222	0.000	0.113	0.170	0.110	0.078	0.123	0.066	0.109	0.061
Ti	0.082	0.060	0.164	0.171	0.167	0.114	0.032	0.085	0.028	0.051	0.081	0.088	0.070
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	1.291	1.255	1.541	1.538	1.341	1.268	1.291	1.245	1.163	1.269	1.184	1.268	1.184
Mn	0.061	0.067	0.038	0.038	0.048	0.057	0.069	0.069	0.101	0.063	0.051	0.048	0.066
Mg	3.461	3.656	3.039	3.060	3.493	3.519	3.542	3.658	3.861	3.632	3.634	3.468	3.651
Ca	1.688	1.562	1.704	1.676	1.630	1.636	1.620	1.638	1.619	1.606	1.679	1.701	1.694
Na	0.343	0.238	0.554	0.480	0.241	0.307	0.183	0.215	0.077	0.206	0.198	0.297	0.198
K	0.065	0.036	0.096	0.108	0.016	0.049	0.044	0.064	0.048	0.040	0.062	0.059	0.044
Total	14.755	14.638	15.042	14.996	15.525	14.715	14.603	14.680	14.626	14.642	14.608	14.686	14.616
Fe/(Fe+Mg)	.272	.255	.336	.334	.277	.265	.267	.254	.231	.259	.246	.268	.245

Note: 3,4 amphibole-biotite aggregate; 6,7 subhedral independent grain; 8-10 surround orthopyroxene; 11,12 surround clinopyroxene.

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	1	2	3*	4*	5*	6	7	8*	9*	10*	11*
SiO ₂	55.79	50.5*	48.8*	48.61	48.70	51.98	51.90	48.63	48.15	48.55	47.98
TiO ₂	0.20	0.57	1.20	1.16	1.17	0.21	0.29	1.16	1.13	1.10	1.25
Al ₂ O ₃	2.28	3.95	5.37	5.61	5.28	2.08	3.36	5.32	5.26	5.28	5.61
Cr ₂ O ₃	0.04	0.00	0.02	0.01	0.02	0.01	0.03	0.00	0.02	0.00	0.02
FeO	17.55	10.60	16.47	15.59	16.23	17.36	18.1*	15.59	16.60	15.79	16.90
MnO	0.41	0.09	0.36	0.37	0.46	0.43	0.47	0.37	0.40	0.37	0.45
MgO	15.9*	16.99	14.16	14.22	14.08	13.05	12.41	14.77	13.77	14.08	13.1*
CaO	11.91	11.50	11.02	10.52	10.71	11.97	10.82	10.58	11.00	10.66	10.61
Na ₂ O	0.16	0.97	1.26	1.19	1.18	0.22	0.22	1.39	1.07	1.39	1.28
K ₂ O	0.06	0.38	0.52	0.48	0.50	0.06	0.19	0.45	0.49	0.45	0.58
Total	100.3*	95.59	99.21	97.76	98.31	97.37	97.83	98.2*	97.96	97.67	97.81
Si	7.557	7.098	6.821	6.848	6.845	7.356	7.307	6.822	6.819	6.860	6.810
Al ^{IV}	0.295	0.55*	0.851	0.89*	0.897	0.296	0.4*	0.840	0.833	0.792	0.847
Tot. Totals	7.652	7.652	7.652	7.652	7.652	7.652	7.652	7.652	7.652	7.652	7.652
Al ^{VI}	0.070	0.077	0.050	0.126	0.068	0.044	0.208	0.047	0.043	0.087	0.095
Ti	0.020	0.058	0.123	0.120	0.120	0.021	0.029	0.119	0.116	0.116	0.129
Cr	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	2.007	1.245	1.922	1.836	1.906	2.052	2.135	1.828	1.97*	1.866	2.003
Mn	0.044	0.008	0.041	0.041	0.053	0.050	0.053	0.041	0.045	0.041	0.054
Mg	2.842	3.557	2.947	2.985	2.950	2.750	2.602	3.088	2.905	2.965	2.778
Ca	1.742	1.727	1.647	1.588	1.613	1.815	1.631	1.589	1.666	1.613	1.612
Na	0.040	0.264	0.340	0.322	0.317	0.058	0.058	0.375	0.291	0.377	0.350
K	0.008	0.066	0.090	0.083	0.086	0.008	0.033	0.078	0.087	0.079	0.104
Total	14.428	14.673	14.812	14.752	14.764	14.454	14.401	14.817	14.779	14.797	14.775
Fe/(Fe+Mg)	.414	.259	.395	.381	.392	.427	.451	.372	.405	.386	.419

Note: 1-5 rim and core around relict clinopyroxene; 6-11 euhedral amphibole; 12 surrounds orthopyroxene.

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Amphiboles

	66B	66B	189	189	175	175	175
	AS	A9	F3	F10	E6	E9	E10
SiO ₂	51.38	49.35	47.79	47.20	51.29	53.56	53.62
TiO ₂	0.23	0.13	0.95	1.15	0.29	0.35	0.33
Al ₂ O ₃	5.82	6.80	5.59	5.90	3.07	2.12	2.73
Cr ₂ O ₃	0.01	0.14	0.00	0.07	0.00	-	-
FeO	9.96	11.05	15.30	16.25	12.79	13.29	13.97
MnO	0.48	-	0.35	0.41	0.47	0.41	0.46
MgO	17.50	16.50	14.67	13.60	16.30	15.72	15.71
CaO	11.61	12.07	10.67	11.37	11.97	11.91	11.28
Na ₂ O	0.19	0.86	1.12	1.16	.47	0.40	0.50
K ₂ O	-	0.06	-	-	-	0.10	0.14
Total	97.18	97.43	96.44	97.11	96.65	97.87	98.81
Si	7.080	6.813	6.761	6.673	7.205	7.377	7.330
Al ^{IV}	0.572	0.839	0.891	0.979	0.447	0.275	0.322
Tet.Total	7.652	7.652	7.652	7.652	7.652	7.652	7.652
Al ^{VI}	0.348	0.265	0.040	0.007	0.059	0.066	0.114
Ti	0.026	0.011	0.103	0.121	0.029	0.037	0.029
Cr	0.000	0.011	0.000	0.007	0.000	-	-
Fe	1.474	1.272	1.811	1.921	1.639	1.329	1.595
Mn	0.055	-	0.040	0.048	0.055	0.044	0.051
Mg	3.593	3.395	3.095	2.867	3.414	3.222	3.201
Ca	1.716	1.782	1.617	1.720	1.800	1.753	1.646
Na	0.051	0.231	0.308	0.319	0.128	0.103	0.132
K	-	0.007	-	-	-	0.015	0.022
Total	14.938	14.648	14.667	14.667	14.780	14.424	14.446
Fe/Fe+Mg	.291	.273	.326	.347	.325	.322	.333

Note: AS, surrounds orthopyroxene; F3, surrounds clinopyroxene; F10, separate grain; E6, E9, E10, rims on clinopyroxene.

HK 3A

	1R	1I	1I	1I	1I	10	10	10	1,0M	1,0M	8,0M	20	30	3R	3I	40	40
B ₁₀ ₂	55.70	57.61	59.04	58.96	59.14	53.85	54.71	53.19	55.34	57.24	54.75	58.07	55.64	55.15	56.21	54.77	56.53
T ₁₀ ₂	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.03	0.02	0.04	0.03	0.02	0.04	0.03
Al ₂ ₃	27.43	27.04	26.75	26.21	26.08	28.96	27.79	28.66	28.00	27.19	27.17	26.19	27.88	27.34	27.80	27.39	27.23
FeO	0.90	0.48	0.31	0.39	0.33	0.65	0.48	0.59	0.96	1.63	1.05	0.39	0.45	1.09	0.40	1.33	1.00
MgO	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00
CaO	9.50	8.05	7.45	7.07	6.61	11.14	10.05	11.18	9.67	8.04	9.27	7.52	9.20	8.69	8.16	9.58	8.96
Na ₂ O	5.90	6.79	7.21	7.46	7.51	5.33	4.90	4.98	5.89	6.73	6.02	6.84	5.88	6.00	6.25	5.98	6.22
K ₂ O	0.19	0.24	0.25	0.24	0.29	0.14	0.20	0.17	0.17	0.26	0.28	0.23	0.20	0.27	0.21	0.13	0.23
P ₂ O ₅	0.03	0.00	0.01	0.00	0.00	0.05	0.05	0.00	0.03	0.00	0.01	0.03	0.03	0.02	0.00	0.07	0.03
Total	99.66	100.23	101.05	100.32	99.96	100.12	98.18	98.79	100.09	101.14	98.60	99.29	99.31	98.58	99.05	99.30	100.24
Si	2.522	2.577	2.613	2.626	2.638	2.436	2.505	2.438	2.498	2.554	2.511	2.614	2.519	2.521	2.541	2.496	2.542
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	1.464	1.425	1.395	1.375	1.371	1.544	1.500	1.549	1.489	1.429	1.468	1.390	1.486	1.473	1.481	1.470	1.444
Fe	0.033	0.017	0.010	0.014	0.012	0.023	0.017	0.021	0.036	0.060	0.039	0.014	0.016	0.042	0.014	0.049	0.037
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Ca	0.459	0.386	0.353	0.337	0.315	0.539	0.492	0.549	0.467	0.383	0.455	0.362	0.446	0.425	0.395	0.466	0.432
Na	0.517	0.588	0.618	0.643	0.649	0.467	0.434	0.442	0.515	0.583	0.534	0.596	0.515	0.531	0.548	0.528	0.542
K	0.010	0.013	0.014	0.013	0.016	0.008	0.011	0.009	0.009	0.014	0.016	0.013	0.010	0.015	0.012	0.006	0.013
P	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Total	5.006	5.005	5.004	5.008	5.001	5.018	4.958	5.009	5.014	5.023	5.023	4.989	4.993	5.007	4.991	5.018	5.010
Al + Si	3.986	4.002	4.008	4.001	4.009	3.980	4.005	3.987	3.987	3.983	3.979	4.004	4.005	3.994	4.022	3.966	3.986
% An	46.6	39.1	35.8	33.9	32.1	53.2	52.5	54.9	47.1	39.1	45.3	37.3	45.9	43.8	41.4	46.6	43.8

APPENDIX G

Biotite Compositions - Contains Bar Pluton

169 H

	10	20	3R	4	5	60	7R	8R	90	10R	11I	12R	13	14	15	16
SiO ₂	38.48	39.05	40.30	40.07	39.95	39.78	39.27	39.66	39.24	39.52	39.17	38.97	38.45	38.25	38.45	38.50
TiO ₂	3.52	3.50	3.12	4.15	4.34	4.20	4.21	4.96	4.75	4.71	4.35	4.66	4.33	4.26	3.62	3.56
Al ₂ O ₃	14.21	14.48	14.55	14.25	14.29	14.60	14.53	14.41	14.38	14.30	14.56	15.09	14.20	14.26	14.25	14.33
Cr ₂ O ₃	0.04	0.02	0.03	0.04	0.03	0.02	0.03	0.04	0.04	0.02	0.01	0.01	0.01	0.02	0.03	0.05
FeO	14.69	14.70	14.46	15.56	15.65	15.79	14.98	15.03	15.77	15.41	16.02	14.47	15.04	14.62	14.47	14.98
MnO	0.11	0.16	0.13	0.14	0.14	0.14	0.11	0.17	0.07	0.12	0.16	0.10	0.14	0.13	0.19	0.11
MgO	15.38	16.05	15.59	15.41	15.55	15.32	15.75	14.90	14.71	14.61	15.28	14.50	14.98	15.12	15.57	15.68
CaO	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.05	0.05	0.02	0.07	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.21	0.20	0.20	0.20	0.22	0.20	0.15	0.19	0.18	0.21	0.22	0.21	0.25	0.18	0.12	0.25
K ₂ O	9.04	9.06	9.02	9.29	8.95	8.94	9.01	8.55	9.19	8.92	8.66	9.18	9.29	9.00	8.95	8.77
P ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	95.68	97.21	97.41	99.14	98.88	99.00	98.96	97.96	98.38	97.64	98.51	97.19	96.70	95.84	95.65	96.23
Si	5.685	5.677	5.814	5.724	5.714	5.688	5.660	5.702	5.659	5.704	5.639	5.661	5.652	5.647	5.684	5.657
Al ^{IV}	2.315	2.323	2.186	2.276	2.286	2.312	2.340	2.298	2.341	2.296	2.361	2.339	2.348	2.353	2.316	2.343
Fe ⁺³	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tot Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.161	0.155	0.287	0.122	0.126	0.148	0.126	0.141	0.101	0.147	0.110	0.244	0.111	0.126	0.166	0.136
Ti	0.390	0.379	0.334	0.444	0.466	0.449	0.457	0.536	0.512	0.511	0.469	0.507	0.474	0.472	0.399	0.392
Cr	0.004	0.000	0.000	0.004	0.000	0.000	0.000	0.004	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.004
Fe ⁺²	1.813	1.783	1.745	1.857	1.874	1.889	1.806	1.806	1.900	1.869	1.926	1.756	1.846	1.803	1.788	1.841
Mn	0.013	0.017	0.013	0.017	0.017	0.012	0.012	0.017	0.008	0.013	0.017	0.008	0.017	0.013	0.021	0.013
Mg	3.387	3.476	3.350	3.279	3.273	3.266	3.384	3.191	3.161	3.158	3.278	3.137	3.283	3.328	3.432	3.432
Ca	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.004	0.004	0.000	0.008	0.000	0.000	0.000	0.000	0.000
Na	0.061	0.051	0.055	0.054	0.059	0.054	0.038	0.050	0.046	0.055	0.059	0.055	0.069	0.047	0.035	0.069
K	1.704	1.676	1.660	1.690	1.630	1.629	1.654	1.566	1.688	1.647	1.588	1.696	1.738	1.694	1.684	1.643
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	15.532	15.536	15.442	15.472	15.443	15.448	15.476	15.315	15.424	15.400	15.455	15.403	15.539	15.483	15.524	15.529
Fe/Fe+Mg	.349	.359	.342	.362	.364	.366	.348	.361	.375	.372	.370	.359	.360	.351	.342	.349

Note: 1-3 core and rim of grain in biotite aggregate; 4,5 small intergranular; 6-8 core to rim of large grain; 9,10 core and rim of small grain; 11,12 large grain; 13-16 small aligned biotites associated only with plagioclase and opaque.

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	1C	2C	3R	4C	5C	6I	7R	8	9	10	11	12	13	14	15	16
SiO ₂	38.23	39.48	37.98	38.80	38.75	39.29	38.65	38.14	38.42	37.89	37.57	37.90	38.76	38.11	38.50	39.23
TiO ₂	5.32	5.56	5.32	4.81	5.62	5.86	4.74	5.76	6.09	6.13	6.23	5.85	4.31	4.22	4.17	4.42
Al ₂ O ₃	14.72	14.90	15.74	15.41	14.81	14.84	14.97	14.82	14.37	14.71	14.64	14.89	15.25	15.00	14.99	15.21
Cr ₂ O ₃	0.03	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.03	0.00	0.02	0.01	0.00
FeO	11.33	11.39	11.77	11.19	10.59	10.76	9.54	10.91	13.06	12.75	12.44	12.09	8.43	8.74	8.57	8.85
MnO	0.06	0.05	0.03	0.09	0.04	0.05	0.03	0.07	0.08	0.05	0.06	0.04	0.04	0.03	0.04	0.04
MgO	16.87	17.53	17.65	18.18	17.93	17.34	18.67	17.05	16.10	15.90	16.05	16.50	19.95	19.86	19.69	19.90
CaO	0.07	0.11	1.27	0.23	0.05	0.09	0.02	0.00	0.15	0.07	0.07	0.16	0.09	0.05	0.02	0.07
Na ₂ O	0.08	0.07	0.20	0.13	0.21	0.18	0.15	0.17	0.21	0.07	0.18	0.10	0.14	0.11	0.22	0.19
K ₂ O	9.87	10.04	9.21	8.41	9.47	9.23	9.21	9.56	9.02	9.80	9.83	9.38	9.74	9.11	9.84	9.89
F ₂ O ₅	0.06	0.03	0.06	0.03	0.02	0.04	0.04	0.00	0.05	0.03	0.06	0.06	0.03	0.02	0.04	0.00
Total	96.65	99.19	99.24	97.27	97.49	97.68	96.03	96.48	97.59	97.41	97.15	97.02	96.73	95.27	96.09	97.79
Si	5.541	5.569	5.373	5.528	5.533	5.579	5.558	5.515	5.533	5.487	5.456	5.479	5.526	5.516	5.539	5.543
Al ^{IV}	2.499	2.431	2.624	2.472	2.467	2.421	2.442	2.485	2.438	2.507	2.502	2.521	2.474	2.484	2.461	2.457
Fe ⁺³	-	-	0.003	-	-	-	-	-	0.029	0.006	0.042	-	-	-	-	-
Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.054	0.045	0.000	0.116	0.023	0.058	0.094	0.041	0.000	0.000	0.000	0.017	0.086	0.072	0.081	0.072
Ti	0.578	0.588	0.564	0.514	0.599	0.625	0.510	0.624	0.659	0.667	0.678	0.632	0.460	0.458	0.447	0.468
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ⁺²	1.169	1.341	1.388	1.330	1.262	1.275	1.144	1.316	1.543	1.536	1.467	1.460	1.004	1.057	1.030	1.044
Mn	0.004	0.004	0.000	0.008	0.004	0.004	0.000	0.004	0.008	0.004	0.004	0.004	0.004	0.000	0.004	0.004
S	3.640	3.685	3.720	3.859	3.814	3.670	4.000	3.676	3.457	3.430	3.474	3.557	4.237	4.280	4.222	4.188
Ca	0.008	0.016	1.191	0.033	0.004	0.012	0.000	0.000	0.021	0.008	0.008	0.021	0.012	0.004	0.000	0.008
Na	0.021	0.016	0.054	0.033	0.054	0.045	0.038	0.046	0.059	0.017	0.047	0.025	0.038	0.029	0.059	0.049
K	1.824	1.805	1.661	1.526	1.723	1.670	1.688	1.762	1.657	1.811	1.820	1.728	1.770	1.677	1.802	1.783
P	0.004	0.000	0.004	0.000	0.000	0.004	0.004	0.000	0.004	0.000	0.004	0.004	0.000	0.000	0.004	0.000
Total	15.503	15.501	15.582	15.420	15.483	15.364	15.478	15.469	15.409	15.473	15.501	15.448	15.610	15.578	15.648	15.616
Fe/Fe+Mg	.273	.267	.272	.256	.249	.258	.222	.264	.313	.310	.303	.291	.192	.198	.196	.199

Note: 1-3 core and rim of small grain; 5-7 core to rim of small intergranular grain; 13, 14, 15, 16, small grains in pyroxene and opaque aggregate clots.

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32

U3-185

	1R	2C	3C	5	6	1	2	3	4	5	6
SiO ₂	37.723	37.706	37.737	38.696	37.200	39.23	39.33	41.52	39.53	40.24	39.73
TiO ₂	4.343	4.694	4.967	4.850	5.268	4.34	4.88	4.70	4.45	4.88	5.06
Al ₂ O ₃	13.228	13.237	13.303	13.501	13.468	13.70	12.99	12.89	13.04	13.67	13.79
Cr ₂ O ₃	-	-	-	-	-	0.04	0.05	0.03	0.07	0.02	0.04
FeO	12.668	12.353	12.466	12.678	12.882	11.81	11.06	11.05	12.26	11.93	14.21
MnO	0.000	0.000	0.000	0.000	0.000	0.18	0.14	0.13	0.17	0.11	0.08
MgO	19.559	19.540	18.732	19.079	18.423	17.23	17.32	18.32	16.77	17.71	16.96
CaO	0.213	0.020	0.015	0.054	0.113	0.25	0.14	0.11	0.12	0.09	0.21
Na ₂ O	0.339	0.271	0.347	0.192	0.404	0.10	0.00	0.12	0.08	0.14	0.14
K ₂ O	9.014	9.454	9.924	9.560	9.596	7.91	9.02	9.38	9.53	9.84	9.61
P ₂ O ₅	-	-	-	-	-	0.00	0.02	0.00	0.01	0.00	0.03
Total	97.293	97.277	97.496	98.613	97.360	94.98	94.55	98.23	96.02	98.63	99.26
Si	5.469	5.470	5.480	5.530	5.419	5.726	5.787	5.863	5.773	5.704	5.626
Al ^{IV}	2.260	2.263	2.276	2.274	2.312	2.274	2.181	2.137	2.227	2.284	2.298
Fe ⁺³	0.271	0.267	0.244	0.196	0.269	-	0.032	-	-	0.012	0.076
Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.000	0.000	0.000	0.000	0.000	0.081	0.000	0.005	0.014	0.000	0.000
Ti	0.495	0.512	0.542	0.521	0.577	0.497	0.540	0.497	0.488	0.520	0.536
Cr	-	-	-	-	-	0.004	0.004	0.000	0.004	0.000	0.004
Fe ⁺²	1.266	1.231	1.270	1.319	1.300	1.439	1.328	1.301	1.496	1.402	1.607
Mn	0.000	0.000	0.000	0.000	0.000	0.021	0.013	0.012	0.017	0.012	0.008
Mg	4.227	4.225	4.054	4.064	4.000	3.747	3.796	3.854	3.647	3.740	3.378
Ca	0.033	0.003	0.002	0.008	0.017	0.034	0.017	0.016	0.017	0.012	0.029
Na	0.095	0.076	0.097	0.053	0.114	0.025	0.000	0.029	0.021	0.037	0.037
K	1.667	1.749	1.838	1.743	1.783	1.469	1.693	1.687	1.774	1.776	1.732
P	-	-	-	-	-	0.000	0.000	0.000	0.000	0.000	0.000
Total	15.735	15.798	15.807	15.709	15.795	15.316	15.390	15.400	15.478	15.499	15.531
Fe/Fe+Mg	.266	.261	.272	.271	.282	.227	.264	.292	.291	.274	.320

Note: 1, 2 rim and core of large grain; 3, core of large subhedral grain; 5 small grain; 6 small grain near amphibole and opaque clots.

Note: 1-4 surround opaques; 5, 6 coexist with amphibole.

189

329-GR

181

	1C	aC	SR	6I	7C	1	2	1	2
SiO ₂	37.312	38.381	37.397	37.872	38.553	36.49	39.38	38.83	38.89
TiO ₂	4.767	5.040	4.431	5.013	5.245	3.36	3.61	4.73	4.66
Al ₂ O ₃	13.451	13.026	13.519	13.332	12.994	14.26	12.79	13.05	13.07
Cr ₂ O ₃	-	-	-	-	-	0.03	0.00	0.04	0.04
FeO	15.962	15.887	15.342	15.957	15.300	14.66	12.56	13.51	13.96
MnO	0.000	0.000	0.000	0.000	0.000	0.24	0.16	0.09	0.11
MgO	15.084	14.894	15.273	14.800	13.041	17.81	17.88	17.09	16.74
CaO	0.060	0.041	0.051	0.009	0.002	0.05	0.17	0.00	0.00
Na ₂ O	0.472	0.342	0.450	0.620	0.586	0.05	0.08	0.23	0.20
K ₂ O	8.482	9.006	9.301	9.159	9.153	7.46	8.33	9.00	8.98
P ₂ O ₅	-	-	-	-	-	0.10	0.05	0.00	0.00
Total	95.595	96.820	95.768	96.785	97.377	94.52	95.03	96.56	96.65
Si	5.571	5.660	5.582	5.601	5.654	5.450	5.784	5.663	5.680
Al ^{IV}	2.367	2.264	2.378	2.327	2.246	2.508	2.211	2.243	2.246
Fe ³⁺	0.062	0.076	0.040	0.072	0.100	0.042	0.005	0.094	0.074
Tet Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.333	0.359	0.497	0.357	0.578	0.377	0.396	0.318	0.310
Cr	-	-	-	-	-	0.000	0.000	0.004	0.000
Fe ²⁺	1.371	1.333	1.473	1.701	1.327	1.786	1.534	1.553	1.628
Mn	0.000	0.000	0.000	0.000	0.000	0.026	0.017	0.008	0.013
Mg	3.336	3.274	3.398	3.262	3.237	3.964	3.914	3.715	3.644
Ca	0.009	0.006	0.008	0.001	0.000	0.004	0.025	0.000	0.000
Na	0.136	0.155	0.130	0.177	0.166	0.013	0.021	0.060	0.056
K	1.615	1.694	1.771	1.728	1.712	1.420	1.560	1.673	1.671
P	-	-	-	-	-	0.008	0.004	0.000	0.000
Total	15.386	15.593	15.681	15.630	15.583	15.598	15.472	15.530	15.521
Fe/Fe+Mg	.373	.374	.360	.377	.371	.316	.282	.307	.318

Note: 1. core large grain near included opaque;
 4. core large grain: 5-7 rim to core of
 large grain.

Note: Coexist
 with amphibole.

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188

175

	1C	2C	3R	4C	5R	6R	1R	2R	4C	5	6C
SiO ₂	37.91	37.35	38.36	38.54	38.42	39.64	37.519	38.396	38.209	36.574	38.578
TiO ₂	5.14	5.06	5.31	5.15	6.01	4.88	4.865	4.509	5.000	4.475	4.659
Al ₂ O ₃	13.14	13.38	13.23	12.86	13.23	13.19	13.917	13.271	13.635	14.372	12.950
Cr ₂ O ₃	0.02	0.01	0.00	0.00	0.00	0.00	-	-	-	-	-
FeO	14.55	14.92	14.29	14.95	14.91	13.72	15.092	15.549	15.644	15.560	15.149
MnO	0.04	0.09	0.06	0.07	0.07	0.06	0.000	0.000	0.000	0.000	0.000
MgO	15.85	15.39	15.79	15.55	14.78	16.88	15.034	15.649	15.610	15.690	16.068
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.441	0.452	0.601	0.625	0.081
Na ₂ O	0.49	0.50	0.10	0.48	0.17	0.24	0.361	0.226	0.362	0.259	0.357
K ₂ O	9.50	9.25	9.73	9.48	9.48	9.68	8.812	8.362	8.281	8.323	9.177
Total	96.84	96.14	96.88	97.09	97.06	98.30	95.645	96.417	97.345	95.881	97.023
Si	5.589	5.566	5.625	5.657	5.629	5.692	5.587	5.653	5.578	5.439	5.659
Al ^{IV}	2.284	2.337	2.285	2.223	2.283	2.229	2.372	2.303	2.346	2.519	2.239
Fe ⁺³	0.127	0.097	0.090	0.120	0.088	0.079	0.041	0.044	0.076	0.042	0.102
Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.566	0.561	0.585	0.564	0.658	0.526	0.544	0.499	0.549	0.500	0.514
Cr	0.000	0.000	0.000	0.000	0.000	0.000	-	-	-	-	-
Fe ⁺²	1.664	1.753	1.661	1.715	1.739	1.568	1.838	1.870	1.834	1.893	1.756
Mn	0.004	0.008	0.004	0.008	0.008	0.004	0.000	0.000	0.000	0.000	0.000
Mg	3.482	3.399	3.451	3.404	3.225	3.611	3.337	3.434	3.397	3.472	3.614
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.071	0.094	0.099	0.012
Na	0.138	0.144	0.025	0.133	0.047	0.067	0.104	0.064	0.102	0.074	0.101
K	1.787	1.750	1.816	1.775	1.771	1.770	1.674	1.570	1.542	1.579	1.717
Total	15.842	15.614	15.542	15.600	15.449	15.547	15.570	15.512	15.521	15.627	15.616
Fe/Fe+Mg	.340	.352	.337	.350	.362	.313	.360	.358	.360	.357	.346

Note: 1-3 cores and rim of large grain; 4-6 core and rim of large grain.

Note: 1, 3 rims of thin blade surrounding opaque; 4, core of large grain; 5, aggregate with amphibole; 6, core large grain.

	1	2	3	4	5	6	7	8	9R
SiO ₂	39.63	38.56	39.48	39.14	38.66	38.51	38.78	39.88	38.71
TiO ₂	4.01	4.29	4.64	2.34	3.46	2.81	4.25	4.41	4.30
Al ₂ O ₃	12.55	12.28	12.26	13.06	13.24	13.06	12.61	12.50	12.80
Cr ₂ O ₃	0.01	0.04	0.02	0.03	0.00	0.00	0.03	0.01	0.01
FeO	15.20	14.78	16.20	16.86	17.36	17.13	16.47	16.62	17.14
MnO	0.16	0.19	0.14	0.21	0.18	0.17	0.18	0.22	0.20
MgO	15.59	15.89	15.07	15.50	14.88	15.14	14.45	14.45	13.87
CaO	0.11	0.09	0.08	0.14	0.13	0.39	0.09	0.05	0.05
Na ₂ O	0.12	0.19	0.14	0.09	0.20	0.09	0.19	0.19	0.09
K ₂ O	8.83	9.29	9.12	8.69	8.86	7.67	9.71	9.68	9.37
P ₂ O ₅	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.04	0.02
Total	96.21	95.59	97.16	96.08	96.97	94.98	96.76	98.06	96.57
Si	5.835	5.735	5.798	5.816	5.714	5.772	5.754	5.823	5.760
Al ^{IV}	2.165	2.152	2.121	2.184	2.286	2.228	2.204	2.151	2.240
Fe ⁺³	-	0.113	0.081	-	-	-	0.042	0.026	-
Tet Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.013	0.000	0.000	0.100	0.018	0.077	0.000	0.000	0.004
Ti	0.440	0.476	0.508	0.257	0.382	0.316	0.470	0.479	0.480
Cr	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe ⁺²	1.871	1.724	1.906	2.092	2.144	2.147	2.001	2.001	2.131
Mn	0.017	0.021	0.017	0.026	0.021	0.018	0.021	0.025	0.021
Mg	3.423	3.522	3.298	3.431	3.276	3.383	3.197	3.145	3.074
Ca	0.017	0.013	0.008	0.021	0.017	0.062	0.013	0.004	0.004
Na	0.034	0.052	0.039	0.021	0.056	0.022	0.052	0.051	0.021
K	1.655	1.759	1.707	1.644	1.670	1.465	1.838	1.799	1.777
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000
Total	15.471	15.572	15.484	15.593	15.584	15.490	15.594	15.509	15.513
Fe/Fe+Mg	.353	.343	.376	.379	.396	.388	.390	.392	.409

Note: generally fringe orthopyroxene and contain opaques.

	1	20	3R	4R	50	6I	7I	8R	9R	10C	11R	12R	13	14	15	16
SiO ₂	38.11	37.21	35.91	37.53	37.47	37.28	37.18	37.73	39.11	38.00	37.08	37.25	38.01	38.46	37.84	37.10
TiO ₂	4.22	4.13	4.06	3.89	4.63	4.73	4.16	4.38	4.16	4.68	4.72	4.61	4.60	4.16	4.11	3.65
Al ₂ O ₃	13.20	12.79	13.55	13.31	13.39	12.70	13.39	13.25	13.28	12.73	13.34	13.34	13.38	13.03	13.46	13.27
Cr ₂ O ₃	0.02	0.08	0.02	0.05	0.00	0.02	0.01	0.03	0.04	0.02	0.02	0.03	0.04	0.02	0.05	0.04
FeO	19.82	18.83	18.67	19.48	18.66	18.81	19.01	19.55	18.72	18.90	18.63	19.65	20.34	18.94	19.34	19.59
MnO	0.22	0.22	0.19	0.23	0.15	0.15	0.18	0.16	0.14	0.14	0.16	0.19	0.17	0.19	0.18	0.20
MgO	12.53	12.59	12.51	12.67	12.71	12.40	12.58	12.61	12.64	12.16	12.30	12.03	12.11	12.82	12.68	12.53
CaO	0.01	0.02	0.03	0.09	0.30	0.00	0.01	0.06	0.05	0.00	0.06	0.07	0.15	0.13	0.09	0.15
Na ₂ O	0.16	0.15	0.12	0.21	0.00	0.28	0.20	0.18	0.11	0.36	0.21	0.15	0.16	0.14	0.18	0.14
K ₂ O	9.42	9.14	9.39	8.87	9.13	9.22	9.25	9.48	9.65	9.34	9.39	9.51	8.41	9.22	9.25	9.22
F ₂ O ₅	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.06
Total	97.70	95.16	94.46	96.32	96.43	95.59	95.96	97.41	97.91	97.04	95.91	96.82	97.37	97.13	97.18	95.96
Si	5.685	5.684	5.541	5.657	5.631	5.669	5.630	5.647	5.772	5.685	5.621	5.615	5.662	5.735	5.651	5.632
Al ^{IV}	2.315	2.299	2.459	2.343	2.368	2.276	2.370	2.336	2.300	2.243	2.379	2.372	2.338	2.265	2.349	2.368
Fe ⁺³	-	0.017	-	-	0.001	0.055	-	0.017	-	0.072	-	0.013	-	-	-	-
Tot Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.006	0.000	0.005	0.019	0.000	0.000	0.016	0.000	0.008	0.000	0.006	0.000	0.010	0.023	0.018	0.007
Ti	0.473	0.470	0.471	0.438	0.520	0.540	0.471	0.492	0.459	0.526	0.534	0.522	0.511	0.463	0.460	0.414
Cr	0.000	0.009	0.000	0.004	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.004	0.000	0.004	0.004
Fe ⁺²	2.470	2.385	2.410	2.455	2.340	2.337	2.494	2.429	2.308	2.290	2.353	2.465	2.531	2.358	2.416	2.486
Mn	0.026	0.027	0.022	0.026	0.018	0.018	0.022	0.017	0.013	0.017	0.018	0.022	0.017	0.021	0.021	0.022
Mg	2.785	2.864	2.876	2.844	2.844	2.808	2.839	2.810	2.780	2.867	2.777	2.703	2.688	2.848	2.823	2.834
Ca	0.000	0.000	0.004	0.013	0.000	0.000	0.000	0.008	0.004	0.000	0.009	0.009	0.021	0.017	0.013	0.022
Na	0.043	0.040	0.031	0.057	0.088	0.080	0.058	0.052	0.030	0.101	0.058	0.044	0.043	0.039	0.048	0.040
K	1.791	1.779	1.848	1.703	1.746	1.786	1.786	1.809	1.814	1.782	1.815	1.827	1.596	1.750	1.762	1.787
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
Total	15.594	15.375	15.668	15.558	15.556	15.569	15.595	15.617	15.493	15.583	15.575	15.591	15.422	15.519	15.565	15.621
Fe/Fe+Mg	.470	.456	.456	.463	.451	.460	.459	.465	.454	.452	.459	.478	.485	.453	.461	.467

Note: 1, 2-4, small grains in amphibole; 5-9, core to rim of large grain; 10-12, core and rim of large grain; 13, 14, 15, 16, small grains.

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	1	2	3C	4R	5R	6C	11C	12	13
SiO ₂	38.53	38.91	39.46	39.39	37.25	38.96	38.59	38.17	38.07
TiO ₂	4.70	4.71	4.91	4.91	4.29	4.72	4.76	5.04	4.58
Al ₂ O ₃	13.50	13.29	12.54	13.06	13.45	12.62	13.80	13.34	13.65
Cr ₂ O ₃	0.02	0.02	0.06	0.05	0.04	0.05	0.00	0.00	0.00
FeO	14.62	14.80	14.57	15.09	15.20	14.13	15.18	14.77	14.77
MnO	0.25	0.22	0.22	0.25	0.21	0.23	0.27	0.25	0.22
MgO	15.70	15.25	16.07	15.52	15.61	15.99	15.55	15.77	16.00
CaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.09	0.10	0.15	0.09	0.10	0.14	0.27	0.17	0.13
K ₂ O	9.60	9.50	9.48	9.13	9.30	9.40	9.59	9.69	9.90
Total	97.00	96.80	97.48	97.49	95.45	96.24	98.01	97.19	97.32
Si	5.647	5.715	5.743	5.730	5.570	5.735	5.613	5.596	5.583
Al ^{IV}	2.331	2.285	2.147	2.237	2.370	2.189	2.365	2.303	2.358
Fe ⁺³	0.022	-	0.110	0.033	0.060	0.076	0.022	0.101	0.059
Tet Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.516	0.517	0.534	0.534	0.482	0.522	0.521	0.555	0.503
Cr	0.000	0.000	0.004	0.004	0.004	0.004	0.000	0.000	0.000
Fe ⁺²	1.767	1.814	1.662	1.803	1.840	1.660	1.822	1.707	1.742
Mn	0.030	0.025	0.025	0.030	0.026	0.026	0.030	0.030	0.025
Mg	3.428	3.336	3.484	3.365	3.480	3.507	3.368	3.448	3.495
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.021	0.025	0.038	0.021	0.026	0.039	0.072	0.047	0.034
K	1.793	1.775	1.759	1.691	1.773	1.762	1.775	1.812	1.851
Total	15.556	15.510	15.507	15.448	15.632	15.520	15.587	15.598	15.657
Fe/Fe+Mg	.343	.352	.337	.353	.353	.332	.354	.344	.341

Note: 1, 2 surround an opaque; 3, 4 coexist with amphibole; 5, 6 rim and core of grain.

UN36

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	1C	2R	3C	4I	5I	6R	7C	8C	9R	10I
SiO ₂	37.91	37.04	37.73	37.98	36.30	36.66	37.69	38.97	38.05	38.57
TiO ₂	4.82	4.86	4.77	4.80	5.58	4.47	4.81	4.92	4.76	4.07
Al ₂ O ₃	12.97	12.88	13.08	12.80	13.07	13.20	13.29	12.70	12.67	12.84
Cr ₂ O ₃	0.07	0.02	0.05	0.04	0.08	0.04	0.04	0.00	0.02	0.01
FeO	16.10	17.77	16.68	17.02	16.82	19.63	17.76	14.41	19.25	16.24
MnO	0.09	0.15	0.14	0.11	0.10	0.22	0.16	0.09	0.14	0.06
MgO	14.05	12.53	13.93	14.68	14.01	11.95	13.38	16.34	12.24	15.63
CaO	0.00	0.03	0.00	0.00	0.02	0.08	0.03	0.00	0.02	0.00
Na ₂ O	0.15	0.11	0.09	0.16	0.07	0.05	0.09	0.09	0.05	0.09
K ₂ O	9.52	9.20	9.61	9.76	9.50	9.39	9.48	9.95	9.53	9.72
Total	95.69	94.60	96.09	97.36	95.54	95.69	96.73	97.48	96.73	97.23
Si	5.680	5.666	5.649	5.623	5.488	5.398	5.625	5.690	5.724	5.688
Al ^{IV}	2.291	2.321	2.306	2.233	2.329	2.375	2.339	2.185	2.242	2.229
Fe ⁺³	0.029	0.013	0.045	0.144	0.183	0.027	0.036	0.125	0.034	0.083
Tet Total	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.541	0.557	0.536	0.534	0.634	0.511	0.539	0.540	0.534	0.450
Cr	0.009	0.000	0.004	0.004	0.009	0.004	0.004	0.000	0.000	0.000
Fe ⁺²	1.984	2.258	2.041	1.963	1.942	2.478	2.181	1.757	2.384	1.917
Mn	0.009	0.013	0.013	0.013	0.009	0.027	0.017	0.008	0.018	0.004
Mg	3.139	2.855	3.105	3.237	3.154	2.721	2.973	3.432	2.740	3.437
Ca	0.000	0.004	0.000	0.000	0.000	0.009	0.004	0.000	0.000	0.000
Na	0.044	0.027	0.026	0.043	0.018	0.013	0.021	0.021	0.013	0.021
K	1.820	1.796	1.832	1.842	1.832	1.829	1.805	1.851	1.827	1.827
Total	15.544	15.515	15.557	15.636	15.597	15.592	15.547	15.609	15.515	15.656
Fe/Fe+Mg	.391	.443	.402	.394	.402	.479	.427	.331	.469	.368

Note: 1, 2 core and rim; 3-5 core toward rim of large grain; 6, 7 rim and center; 8-10 core to rim.

	10	20	3I	4I	50	6
SiO ₂	37.34	37.72	38.04	37.36	36.60	37.35
TiO ₂	5.25	5.14	4.79	4.62	5.27	4.21
Al ₂ O ₃	13.13	13.49	13.44	13.94	13.98	13.24
Cr ₂ O ₃	0.03	0.00	0.01	0.01	0.00	0.00
FeO	15.60	15.02	14.77	14.64	15.23	14.05
MnO	0.12	0.20	0.14	0.14	0.17	0.14
MgO	14.82	14.68	15.61	15.63	14.70	16.77
CaO	0.03	0.06	0.02	0.00	0.04	0.10
Na ₂ O	0.27	0.21	0.27	0.21	0.18	0.07
K ₂ O	9.54	9.09	9.57	9.24	8.71	7.73
P ₂ O ₅	0.00	0.01	0.00	0.00	0.00	0.05
Total	96.14	95.62	96.65	95.79	94.88	93.71
Si	5.570	5.613	5.611	5.548	5.495	5.575
Al ^{IV}	2.308	2.368	2.333	2.440	2.472	2.425
Fe ⁺³	0.122	0.019	0.056	0.012	0.033	-
Tet Total	8.000	8.000	8.000	8.000	8.000	8.000
Al ^{VI}	0.000	0.000	0.000	0.000	0.000	0.045
Ti	0.586	0.572	0.528	0.514	0.595	0.473
Cr	0.000	0.000	0.000	0.000	0.000	0.000
Fe ⁺²	1.822	1.851	1.762	1.805	1.880	1.651
Mn	0.013	0.021	0.017	0.017	0.018	0.013
Mg	3.297	3.254	3.433	3.456	3.288	3.731
Ca	0.004	0.008	0.000	0.000	0.004	0.013
Na	0.079	0.057	0.073	0.061	0.053	0.017
K	1.813	1.725	1.801	1.748	1.666	1.467
P	0.000	0.000	0.000	0.000	0.000	0.004
Total	15.613	15.489	15.615	15.600	15.502	15.414
Fe/Fe+Mg	.371	.365	.346	.345	.368	.307

Note: generally in aggregates of biotite, amphibole and opaques; 5, individual subhedral grain.

Chemical analyses of iron-titanium oxides in rocks from Unalaska Island

189 H

	A	C	D	E	F	G	B	H	I	J	K	M	N
SiO ₂	0.06	0.16	0.16	0.16	0.14	0.56	0.15	0.15	0.16	0.11	0.09	0.09	0.09
TiO ₂	2.43	2.20	2.57	3.21	4.02	3.00	50.12	47.38	48.69	49.81	49.39	46.09	49.38
Al ₂ O ₃	3.00	2.96	3.44	3.75	2.44	3.42	0.48	0.59	0.54	0.60	0.43	0.78	0.62
Cr ₂ O ₃	0.33	0.30	0.32	0.28	0.33	0.27	0.00	0.01	0.02	0.02	0.05	0.04	0.00
FeO	87.88	88.09	85.84	84.73	85.67	83.89	47.96	49.45	48.72	48.70	47.73	50.27	48.48
MnO	0.08	0.03	0.07	0.13	0.19	0.15	1.38	1.29	1.19	1.26	1.20	1.09	1.20
MgO	0.21	0.20	0.30	1.03	0.30	0.55	0.13	0.25	0.21	0.28	0.08	0.63	0.11
Total	94.00	93.95	92.69	93.29	93.08	91.84	100.22	99.13	99.53	100.78	98.97	98.98	99.89
FeO	33.57	33.55	33.32	32.94	34.42	33.45	-	-	-	-	-	-	-
Fe ₂ O ₃	60.36	60.62	58.37	57.55	56.96	56.06	-	-	-	-	-	-	-
Total	100.04	100.02	98.55	99.05	98.80	97.46	-	-	-	-	-	-	-
% Ulv.	6.91	6.28	7.42	9.15	11.62	8.86	-	-	-	-	-	-	-
% R ₂ O ₃	-	-	-	-	-	-	5.25	9.76	7.47	6.67	5.54	12.69	6.56
Ilmenite Basis													
FeO	32.07	32.10	31.66	30.89	31.90	31.20	43.62	41.03	42.40	43.15	43.16	39.33	43.10
Fe ₂ O ₃	62.03	62.23	60.22	59.83	59.75	58.55	4.82	9.35	7.03	6.17	5.07	12.16	5.98
Total	100.21	100.18	98.74	99.28	99.07	97.70	100.70	100.05	100.24	101.40	99.47	100.21	100.48

Note: A, C, D, independent grains; E, enclosed in pyroxene; F, G, in contact with ilmenite (H, I); B, interstitial between pyroxenes; H, I, in contact with (F, G); J, contact with biotite; K, in pyroxene clot; M, independent grain; N, lamellae in magnetite.

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	A1	A2	A3	A4	B1	B2	B3	B4	D	F	G	H	J
SiO ₂	0.05	0.02	0.06	0.06	0.16	0.09	0.13	0.15	0.04	0.09	0.29	0.17	0.15
TiO ₂	45.53	49.37	49.55	49.83	0.59	0.69	2.23	2.54	46.58	47.89	1.16	1.74	1.23
Al ₂ O ₃	0.75	0.92	0.91	0.97	2.48	2.48	2.99	2.75	0.84	0.87	1.53	2.57	1.73
Cr ₂ O ₃	0.00	0.02	0.04	0.00	0.23	0.25	0.25	0.21	0.00	0.18	0.94	0.12	0.92
FeO	48.07	48.18	47.68	48.23	91.87	91.73	89.47	89.89	48.12	48.13	90.91	91.70	89.99
MnO	1.34	1.26	1.58	1.39	0.09	0.10	0.24	0.30	1.60	1.80	0.12	0.12	0.10
MgO	0.62	0.73	0.60	0.63	0.00	0.00	0.06	0.03	0.30	0.09	0.01	0.13	0.02
Total	96.36	100.51	100.42	101.11	95.43	95.54	95.37	95.87	97.48	99.04	94.96	96.54	94.14
FeO	-	-	-	-	32.83	32.79	34.02	34.43	-	-	33.14	34.00	32.79
Fe ₂ O ₃	-	-	-	-	65.62	65.51	61.63	61.64	-	-	64.20	64.13	63.58
Total	-	-	-	-	102.00	101.91	101.55	102.05	-	-	101.39	102.98	100.52
% Ulv.	-	-	-	-	1.66	1.94	6.27	7.13	-	-	3.32	4.85	3.53
% R ₂ O ₃	11.43	7.93	7.31	7.47	-	-	-	-	10.20	8.80	-	-	-
Ilmenite Basis													
FeO	38.54	41.84	41.96	42.35	32.35	32.31	32.58	32.79	39.78	41.19	32.22	32.82	31.93
Fe ₂ O ₃	10.59	7.04	6.36	6.53	66.15	66.04	63.23	63.46	9.27	7.71	65.23	65.44	64.53
Total	97.42	101.20	101.06	101.76	102.05	101.96	101.71	102.23	98.41	99.82	101.50	103.11	100.61

Note: A1-A4, single grain; B1-B4, core to rim of magnetite; D, zoned ilmenite; F, ilmenite lath aligned with parting in clinopyroxene; G, J, enclosed in clinopyroxene; H, in plagioclase.

	1	2	3	4	5	1T	2T	7	8	9	10	11	3T	12	13	14	15	16	17
SiO ₂	0.16	0.07	0.07	0.16	0.06	0.10	0.16	0.30	0.01	0.10	0.16	0.09	0.10	0.03	0.08	0.19	0.14	0.00	0.47
TiO ₂	0.72	0.87	2.05	1.02	0.71	3.91	1.21	0.01	45.02	44.39	0.66	0.42	2.81	43.68	43.84	41.15	41.36	42.54	41.45
Al ₂ O ₃	1.84	1.96	2.25	1.91	2.05	2.17	1.98	0.97	0.61	0.66	1.64	1.05	2.39	0.53	0.61	0.50	0.63	0.59	0.59
Cr ₂ O ₃	0.07	0.12	0.08	0.11	0.04	0.04	0.06	0.00	0.00	0.00	0.04	0.07	0.12	0.00	0.00	0.00	0.00	0.02	0.00
FeO	90.79	90.91	89.88	91.07	91.12	87.36	89.04	89.61	44.26	44.14	91.91	92.75	87.72	49.33	49.42	55.53	54.10	51.88	54.59
MnO	0.14	0.15	0.19	0.07	0.12	0.12	0.15	0.01	9.53	9.29	0.15	0.07	0.11	4.62	4.62	2.81	2.84	4.14	1.79
MgO	0.00	0.00	0.06	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.04
Total	93.72	94.08	94.58	94.34	94.36	93.71	92.61	90.90	99.43	98.57	94.56	94.45	93.32	98.19	98.56	98.18	99.07	99.18	98.93
FeO	32.24	32.38	33.48	32.79	31.97	34.98	32.30	-	-	-	32.43	32.10	33.83	-	-	-	-	-	-
Fe ₂ O ₃	65.07	65.05	62.69	64.78	65.74	58.22	63.06	-	-	-	66.10	67.41	59.89	-	-	-	-	-	-
Total	100.24	100.60	100.87	100.84	100.95	99.54	98.92	-	-	-	101.18	101.21	99.32	-	-	-	-	-	-
X Ulv.	2.07	2.48	5.82	2.92	2.02	11.25	3.52	-	-	-	1.88	1.20	8.10	-	-	-	-	-	-
X Fe ₂ O ₃	-	-	-	-	-	-	-	99.19	14.99	15.28	-	-	-	16.41	16.34	21.05	21.53	19.62	20.46
Ilmenite Basis																			
FeO	31.68	31.81	32.19	32.05	31.50	32.56	31.45	0.37	30.84	30.63	31.91	31.78	32.07	34.64	34.84	34.39	34.49	34.06	35.95
Fe ₂ O ₃	65.69	65.69	64.11	65.80	66.26	60.91	64.01	99.18	14.91	15.01	66.68	67.76	61.85	16.33	16.20	21.27	21.80	19.80	20.71
Total	100.30	100.67	101.00	100.92	101.00	99.81	99.02	100.84	100.92	100.08	101.24	101.24	99.52	99.83	100.19	100.31	101.26	101.15	101.00

Note: 1-5 small subhedral grains; 1T, 2T small grains in pyroxene; 7, 10, 11, in biotite; 8, 9, in biotite; 3T opaque clots; 12, 13, grains in biotite; 14, 15 individual laths; 16, 17, independent grains.

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189-2

32 BAP

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	1	2	3	4	5	6
SiO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.07	0.05	0.06	0.28
TiO ₂	44.13	0.80	22.28	1.52	42.18	43.38	42.76	1.14	42.13	0.57	1.02	2.20	1.21	0.74	1.50	95.91
Al ₂ O ₃	0.05	0.82	0.35	0.61	0.02	0.03	0.08	0.75	0.04	0.56	0.80	0.59	0.66	0.73	0.80	0.28
Cr ₂ O ₃	0.00	0.24	0.17	0.23	0.03	0.03	0.00	0.17	0.02	0.21	0.00	0.01	0.00	0.07	0.02	0.00
FeO	47.52	92.66	65.48	91.90	47.56	47.43	47.06	91.34	47.43	90.76	90.75	90.00	88.13	89.30	86.08	0.43
MnO	2.74	0.01	1.28	0.04	4.09	2.61	2.77	0.04	3.16	0.03	0.26	0.35	0.22	0.07	0.33	0.00
MgO	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	95.27	94.54	89.94	94.32	95.06	94.23	93.48	93.46	93.21	92.14	92.87	93.19	90.29	90.96	88.79	96.90
FeO	-	32.37	47.91	32.86	-	-	-	32.26	-	31.31	31.80	32.81	31.17	-	-	-
Fe ₂ O ₃	-	67.01	19.52	65.62	-	-	-	65.66	-	66.07	65.51	63.56	63.31	-	-	-
Total	-	101.25	91.51	100.88	-	-	-	100.02	-	98.75	99.43	99.56	96.64	-	-	-
% Oliv.	-	2.28	68.74	4.35	-	-	-	3.29	-	1.67	2.96	6.38	3.62	-	-	-
% H ₂ O ₃	11.93	-	-	-	15.42	12.49	13.03	-	14.47	-	-	-	-	98.41	96.81	-
Ilmenite Basis																
FeO	36.84	31.89	34.57	31.94	33.79	36.37	35.65	31.58	34.68	30.97	31.16	31.46	30.39	0.67	1.10	-
Fe ₂ O ₃	11.87	67.54	34.35	66.63	15.30	12.30	12.68	66.42	14.16	66.45	66.23	65.06	64.18	98.51	94.45	-
Total	95.67	101.30	93.00	100.97	95.41	94.72	93.94	100.10	94.19	98.79	99.51	99.71	96.73	100.84	98.26	-

Note: G1, lath in biotite; G2, G3, magnetite with ilmenite lamellae; G4, large grain with G5 and G6 ilmenite lamellae; G7 small homogenous grain in biotite; G8, G9, large grain with ilmenite lamellae; G10, small interstitial grain.

Note: 1, 2, 3, subhedral grains with ilmenite lamellae; 4, 5, in biotite; 6, rutile associated with sphene in hematite.

32 BGR

93 C

	1	2	3	4	AB	C	D	G	H	J	N	O	P
SiO ₂	0.05	0.14	0.02	0.21	0.27	0.04	0.00	0.04	0.02	0.14	0.16	0.10	0.09
TiO ₂	1.93	1.27	1.36	88.60	0.96	0.68	1.17	1.57	0.57	0.83	0.52	2.16	0.78
Al ₂ O ₃	0.85	0.77	0.94	2.45	1.23	0.97	1.00	1.38	1.15	1.48	1.43	1.03	1.04
Cr ₂ O ₃	0.52	0.18	0.43	0.02	0.16	0.11	0.07	0.13	0.08	0.04	0.02	0.09	0.10
FeO	90.20	89.48	90.19	1.30	92.88	91.86	91.36	90.68	92.13	93.28	91.97	92.59	93.59
MnO	0.18	0.12	0.12	0.00	0.06	0.08	0.32	0.08	0.05	0.12	0.00	0.03	0.03
MgO	0.00	0.00	0.00	0.18	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
Total	93.73	91.96	93.06	92.76	95.57	93.75	93.92	93.88	93.99	95.86	94.11	96.00	95.68
FeO	32.97	31.98	32.29	-	33.17	32.00	32.20	32.87	32.03	32.96	32.28	34.17	32.80
Fe ₂ O ₃	63.61	63.91	64.35	-	66.36	66.52	65.75	64.25	66.80	67.04	66.34	64.93	67.56
Total	100.11	98.37	99.51	-	102.23	100.40	100.51	100.32	100.70	102.63	100.75	102.51	102.46
% Ulv.	5.56	3.74	3.94	-	2.73	1.95	3.35	4.50	1.63	2.34	1.49	6.08	2.20
% R ₂ O ₃	-	-	-	-	-	-	-	-	-	-	-	-	-
Ilmenite Basis													
FeO	31.77	31.10	31.46	-	32.38	31.56	31.50	31.90	31.67	32.35	31.84	32.80	32.27
Fe ₂ O ₃	64.94	64.88	65.28	-	67.24	67.01	66.53	65.33	67.20	67.72	66.83	66.45	68.16
Total	100.24	98.46	99.61	-	102.32	100.45	100.59	100.43	100.74	102.70	100.80	102.66	102.53

Note: 1, 2, small grains in amphibole; 3 large grain with irregular zones of rutile and sphene; 4, rutile in magnetite.

Note: A, B, C, in amphibole; D, large grain in amphibole; G, large grain in amphibole with thin ilmenite lamellae (rare); H, small grain; J, average of 3 intergrown with amphibole in a vein; N, O, P, small granular grains in amphibolitized volcanic in contact with 93C.

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	AC	AR	BC	BR	C1	C2	D1	D2	D3	D4	D5	E1	E2	E3	F1	G
SiO ₂	0.10	0.09	0.04	0.05	0.11	0.07	0.21	0.21	0.20	0.19	0.16	0.04	0.07	0.00	0.18	0.09
TiO ₂	3.81	3.00	44.35	44.41	43.93	45.38	2.18	1.25	3.44	3.01	15.60	43.77	43.07	45.12	2.88	42.30
Al ₂ O ₃	2.17	1.54	0.67	0.66	0.57	0.55	1.11	1.34	2.12	2.27	1.77	0.70	0.67	0.66	1.88	0.51
Cr ₂ O ₃	0.29	0.37	0.02	0.02	0.04	0.10	0.35	0.60	0.34	0.34	0.32	0.00	0.00	0.01	0.35	0.09
FeO	88.45	88.84	49.77	48.99	50.23	48.98	87.54	88.47	88.54	87.17	80.45	50.70	50.15	49.61	86.61	52.47
MnO	0.18	0.31	2.95	2.66	2.86	2.98	0.58	0.08	0.27	0.39	1.09	3.05	3.07	3.27	0.36	2.79
MgO	0.03	0.06	0.18	0.17	0.20	0.17	0.03	0.02	0.04	0.03	0.01	0.12	0.11	0.15	0.00	0.20
Total	95.02	94.20	97.96	96.96	97.93	98.24	92.00	91.97	94.95	93.39	99.38	98.37	97.13	98.82	92.26	98.45
FeO	35.22	33.98	-	-	-	-	32.40	32.13	34.89	-	46.00	-	-	-	33.42	-
Fe ₂ O ₃	59.15	60.98	-	-	-	-	61.29	62.62	59.63	-	38.29	-	-	-	59.11	-
Total	100.95	100.33	-	-	-	-	98.15	98.25	100.93	-	103.24	-	-	-	98.18	-
% Ulv.	10.81	8.59	-	-	-	-	6.43	3.68	9.80	-	42.96	-	-	-	8.44	-
% Fe ₂ O ₃	-	-	15.02	13.92	15.63	13.05	-	-	-	-	-	16.51	16.72	14.31	-	19.35
Ilmenite Basis																
FeO	32.86	32.11	36.62	37.00	36.38	37.57	30.92	31.21	32.67	-	36.53	36.11	35.51	37.00	31.55	34.97
Fe ₂ O ₃	61.78	63.05	14.61	13.33	15.39	12.68	62.92	63.64	62.09	-	48.81	16.22	16.27	14.02	61.19	19.45
Total	101.22	100.53	99.44	98.30	99.48	99.50	98.30	98.35	101.17	-	104.29	100.01	98.77	100.23	98.39	100.40

Note: AC, AR, core and rim of grain in amphibole; BC, BR, core and rim of independent grain; C1, C2, large ilmenite; D1, D2, rhombic grain in clinopyroxene; D3, D4, core of large grain; D5, edge of same; E1-E3, ilmenite in contact with D3 and D4; F1, G, in orthopyroxene.

	1	2	3	4	1T	5	6	7	8	9	2T	10	11	3T	12	13	Al3	Al4	Al5
SiO ₂	0.00	0.00	0.02	0.05	0.20	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.30	0.00	0.06	0.00	0.00	0.00
TiO ₂	1.87	2.75	1.91	2.85	10.02	3.44	45.16	4.24	45.72	42.35	25.51	49.00	1.94	5.27	1.59	1.98	1.47	1.53	0.45
Al ₂ O ₃	0.84	0.93	0.90	0.77	0.73	1.71	0.57	1.17	0.57	0.51	0.59	0.39	0.70	0.80	0.77	0.93	0.18	0.20	0.26
Cr ₂ O ₃	0.62	0.68	0.93	1.07	0.80	0.39	0.02	0.37	0.00	0.00	0.00	0.00	0.73	0.62	0.68	0.76	0.66	0.20	0.12
FeO	89.45	87.32	87.79	87.85	82.82	86.16	46.64	86.55	41.45	45.85	64.99	48.90	87.38	85.43	87.27	87.28	89.25	89.14	90.19
MnO	0.20	0.43	0.21	0.36	1.86	0.56	5.98	0.54	9.65	5.17	0.89	0.30	0.18	0.54	0.37	0.39	0.21	0.22	0.03
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.27	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	92.98	92.11	91.76	92.95	96.43	92.26	98.56	92.88	97.66	93.96	91.98	98.59	90.93	92.96	90.68	91.40	91.83	91.36	91.08
FeO	32.58	32.83	32.22	33.30	39.33	33.45	-	34.31	-	-	51.94	-	31.95	35.54	31.39	32.04	31.73	31.62	30.81
Fe ₂ O ₃	65.11	60.56	61.76	60.63	48.34	58.58	-	58.06	-	-	14.50	-	61.60	55.45	62.11	61.40	63.93	63.93	65.99
Total	99.32	98.18	97.95	99.03	101.23	98.13	-	98.69	-	-	95.43	-	97.10	98.52	96.91	97.56	98.18	97.70	97.66
% Ulv.	5.42	8.06	5.62	8.30	28.47	10.03	-	12.33	-	-	26.77	-	5.76	15.51	4.73	5.85	4.33	4.53	1.33
% H ₂ O ₃	-	-	-	-	-	-	14.04	-	12.17	15.42	-	6.07	-	-	-	-	-	-	-
Ilmenite Basis																			
FeO	31.46	31.18	31.06	31.55	33.17	31.39	34.20	31.76	30.86	32.69	36.66	43.76	30.79	32.14	30.43	30.81	30.85	30.71	30.54
Fe ₂ O ₃	64.45	62.39	63.05	62.57	55.18	60.87	13.83	60.89	11.77	14.63	31.48	5.71	62.89	59.22	63.17	62.77	64.91	64.94	66.29
Total	99.44	98.36	98.08	99.22	101.96	98.36	99.96	98.98	98.84	95.44	95.13	99.16	97.23	98.89	97.01	97.70	98.28	97.80	97.69

Note: 1, 2, 3, 4, 1T, small grains in amphibole; 5, 6, sides of single large grain in contact enclosed in biotite; 7, 8-9, same pair; 2T, lamellae in 7; 10, in biotite; 11, 12 3T, 13, Al3, intergrown with amphibole; Al4, Al5, rhombic grain in biotite.

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO ₂	0.05	0.77	0.01	0.00	0.00	0.00	0.08	0.00	0.00	0.10	0.07	0.02	0.01
TiO ₂	46.36	44.82	42.98	48.53	47.86	47.17	46.84	47.17	46.56	1.84	1.57	2.04	46.90
Al ₂ O ₃	0.48	0.56	0.52	0.60	0.43	0.55	0.59	0.54	0.55	1.21	1.40	1.20	0.63
Cr ₂ O ₃	0.02	0.02	0.00	0.01	0.02	0.00	0.01	0.02	0.05	0.29	0.29	0.59	0.07
FeO	45.75	47.59	45.41	48.83	47.50	47.16	46.20	46.29	47.34	85.22	88.66	85.47	47.73
MnO	2.40	2.27	2.15	2.15	2.32	2.39	2.57	2.58	1.69	0.30	0.28	0.38	3.02
MgO	0.01	0.34	0.06	0.18	0.05	0.14	0.11	0.06	0.36	0.00	0.03	0.12	0.08
Total	95.09	96.38	91.13	100.30	98.20	97.42	96.40	96.66	96.55	88.96	92.30	89.82	98.43
FeO	-	-	-	-	-	-	-	-	-	-	32.14	-	-
Fe ₂ O ₃	-	-	-	-	-	-	-	-	-	-	62.82	-	-
Total	-	-	-	-	-	-	-	-	-	-	98.60	-	-
% Ulv.	-	-	-	-	-	-	-	-	-	-	4.58	-	-
% R ₂ O ₃	7.89	10.89	11.21	8.91	8.04	8.80	8.28	8.00	9.36	96.03	-	95.88	10.31
Ilmenite Basis													
FeO	39.30	38.32	36.38	41.14	40.60	39.75	39.42	39.70	39.52	1.48	31.14	1.27	38.99
Fe ₂ O ₃	7.18	10.30	10.04	8.54	7.67	8.24	7.54	7.33	8.69	93.07	63.93	93.58	9.72
Total	95.80	97.40	92.14	101.15	98.95	98.24	97.16	97.40	97.42	98.29	98.71	99.20	99.42

B1	B2	B4	B5	B7	B8	B10	B11	B13	B14
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45.04	44.64	0.84	0.63	44.63	0.45	2.11	43.20	0.38	43.10
0.04	0.16	0.39	0.38	0.19	0.45	0.31	0.07	0.53	0.13
0.00	0.00	0.21	0.27	0.04	0.22	0.08	0.00	0.30	0.03
49.66	50.38	93.10	92.55	51.19	91.17	93.05	49.95	93.85	49.76
2.44	2.45	0.03	0.02	2.37	0.05	0.25	2.44	0.04	2.62
0.00	0.00	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.14
97.89	98.34	94.56	93.86	99.24	92.34	95.88	96.37	95.11	96.54
-	-	32.24	31.92	-	31.24	33.62	-	32.13	-
-	-	67.53	67.38	-	66.60	66.05	-	68.60	-
-	-	101.34	100.60	-	99.01	102.42	-	101.98	-
-	-	2.40	1.81	-	1.31	5.95	-	1.03	-
12.61	13.88	-	-	14.85	-	-	14.96	-	15.41
38.03	37.66	31.84	31.55	37.50	30.98	32.35	36.38	31.90	35.86
12.92	14.13	68.09	67.80	15.21	66.90	67.46	15.08	68.85	15.45
98.47	99.04	101.40	100.65	100.07	99.05	102.56	97.17	102.00	97.33

Note: 1-8, enclosed in biotites; 9, lath shaped grain; 10-12, in amphibole with thin oriented ilmenite (13); B1, B2, laths in biotite; B4, B5, large grain in biotite with B, lamellae; B10, B11, independent grains; B13, grain with ilmenite lamellae B14.

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179 E

	1	2	3	4	5	6	7	8
SiO ₂	0.01	0.10	0.14	0.09	0.16	0.27	0.13	0.05
TiO ₂	45.51	47.15	46.49	46.36	0.90	1.35	46.74	1.12
Al ₂ O ₃	0.75	0.80	0.94	0.84	2.47	2.28	0.73	1.90
Cr ₂ O ₃	0.01	0.01	0.02	0.06	0.25	0.21	0.04	0.28
FeO	50.82	47.32	47.34	49.31	91.10	92.14	49.36	90.73
MnO	1.22	3.43	2.41	2.02	0.14	0.08	1.12	0.13
MgO	0.04	0.01	0.00	0.21	0.02	0.11	0.34	0.00
Total	98.36	98.83	97.35	98.89	95.05	96.43	98.46	94.21
FeO	-	-	-	-	32.89	33.78	-	32.62
Fe ₂ O ₃	-	-	-	-	64.70	64.86	-	64.58
Total	-	-	-	-	101.53	102.94	-	100.68
% Ulv.	-	-	-	-	2.55	3.78	-	3.19
% R ₂ O ₃	13.02	9.98	9.83	11.79	-	-	10.58	-
Ilmenite Basis								
FeO	39.63	39.03	39.53	39.38	32.22	32.76	40.45	31.91
Fe ₂ O ₃	12.44	9.22	8.68	11.04	65.44	66.00	9.91	65.37
Total	99.61	99.75	98.21	100.00	101.60	103.06	99.46	100.76

Note: 1-4, enclosed in biotite; 5, 6, large grain with thin ilmenite lamellae;
7, 8, in clinopyroxene.

UN 36

	A	B	D	E	F	G	H	I	J	BD	B1	B2	BF
SiO ₂	0.03	0.05	0.10	0.16	0.17	0.16	0.23	0.27	0.21	0.29	0.25	0.05	0.79
TiO ₂	46.86	46.55	47.35	1.80	1.16	10.72	10.66	47.23	46.21	2.90	0.61	48.66	48.93
Al ₂ O ₃	0.79	0.75	0.91	2.36	2.04	2.10	1.93	0.84	0.79	1.35	1.94	0.75	0.89
Cr ₂ O ₃	0.09	0.13	0.13	0.64	0.67	0.63	0.68	0.02	0.07	0.46	0.45	0.04	0.04
FeO	48.07	46.36	46.79	91.61	93.24	74.99	75.93	49.94	49.85	87.64	91.30	48.78	46.07
MnO	2.97	3.04	4.75	0.10	0.10	1.30	1.29	2.41	2.22	0.76	0.13	2.28	1.92
MgO	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.07	0.00	0.00	0.04	0.26
Total	98.82	96.87	100.03	96.67	97.38	89.90	90.71	100.71	99.41	93.40	94.68	100.00	98.89
FeO	-	-	-	-	-	38.45	38.74	-	-	33.48	32.60	-	-
Fe ₂ O ₃	-	-	-	-	-	40.61	41.34	-	-	60.19	65.24	-	-
Total	-	-	-	-	-	93.97	94.88	-	-	99.43	101.22	-	-
% Ulv.	-	-	-	-	-	32.47	32.10	-	-	8.45	1.74	-	-
% R ₂ O ₃	10.73	9.40	10.77	-	-	-	-	11.19	12.18	-	-	8.78	5.09
Ilmenite Basis													
FeO	39.13	38.84	37.89	-	-	31.91	32.17	40.35	39.43	31.51	32.03	41.44	42.54
Fe ₂ O ₃	9.93	9.36	9.89	-	-	47.88	48.63	10.65	11.58	62.38	65.87	8.16	3.93
Total	99.82	98.72	101.02	-	-	94.70	95.60	101.77	100.58	99.65	101.28	101.42	99.30

Note: A, B, D, rim on magnetite BD enclosed in biotite; E, F, large grain with titanomagnetite core (G,H), I,J, small grain in contact with plagioclase; B1, B2 in contact with BD; BF separate grain.

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MK3A

	1	2	3	4	5	6	7	9	10	11	12	13
SiO ₂	0.13	0.30	0.32	0.24	0.10	0.19	0.21	0.27	0.16	0.19	0.43	0.23
TiO ₂	5.91	7.49	10.75	10.43	6.57	6.31	7.91	8.82	7.59	6.76	5.32	6.92
Al ₂ O ₃	5.05	3.46	2.54	2.36	6.27	6.16	4.30	5.53	6.76	8.31	3.68	6.49
Cr ₂ O ₃	0.07	0.02	0.02	0.02	0.04	0.06	0.04	0.06	0.08	0.07	0.00	0.05
FeO	82.11	83.36	75.33	76.34	78.71	80.02	79.31	81.18	80.83	78.83	81.57	80.82
MnO	0.92	0.81	1.45	1.06	0.98	0.90	1.02	0.48	0.44	0.51	0.80	0.54
MgO	0.90	1.05	0.59	0.67	1.72	1.61	1.09	1.99	1.50	2.04	0.61	1.57
Total	95.09	96.49	91.00	91.12	94.41	95.26	93.88	98.33	97.36	96.71	92.40	96.62
FeO	35.42	37.13	38.07	37.98	34.58	34.98	36.35	-	-	35.89	34.77	36.49
Fe ₂ O ₃	51.89	51.37	41.41	42.63	49.05	50.05	47.74	-	-	47.72	52.01	49.27
Total	100.29	101.63	95.15	95.39	99.31	100.76	98.66	-	-	101.49	97.62	101.56
% Ulv.	16.48	20.85	32.12	31.02	18.23	17.43	22.48	-	-	18.18	15.54	18.86
% R ₂ O ₃	-	-	-	-	-	-	-	-	-	-	-	-
Ilmenite Basis												
FeO	31.78	32.41	31.38	31.54	30.56	31.05	31.45	-	-	31.69	31.24	32.16
Fe ₂ O ₃	55.94	56.62	48.85	49.79	53.51	54.42	53.19	-	-	52.39	55.93	54.08
Total	100.70	102.16	95.90	96.11	99.75	100.70	99.21	-	-	101.96	98.01	102.04

Note: 1, 2, 5, 6, in groundmass; 3, 4, medium size phenocrysts; 6, 7, core and rim of large phenocryst; 9-11, rim to core in amphibole cumulate; 12, 13, rim and core of grain in cumulate.

SPINELS

MK-15

	1a	1b	2C	2I	2R	3, C, GM	3, R, GM	4C	4R
SiO ₂	0.27	0.22	0.26	0.21	0.25	0.21	0.24	0.28	0.27
TiO ₂	2.18	2.23	6.76	7.09	7.70	6.86	7.19	3.02	4.85
Al ₂ O ₃	15.98	14.92	3.51	3.66	3.25	2.30	2.16	10.50	7.02
Cr ₂ O ₃	18.00	18.11	10.98	10.54	7.50	10.81	5.90	17.57	11.25
FeO	50.88	53.30	70.31	69.64	73.36	71.07	76.82	58.92	67.09
MnO	0.33	0.41	0.45	0.47	0.47	0.50	0.49	0.47	0.46
MgO	7.86	7.66	3.68	3.55	3.72	2.08	2.11	6.16	4.98
ZnO	0.21	0.05	0.13	0.32	0.29	0.66	0.47	0.12	0.01
Total	95.71	96.89	96.09	95.48	96.54	94.48	95.38	97.04	95.92

	5C	5R	6C	6R	6R	7 GM	8 GM	9, C, GM	9, R, GM
SiO ₂	.20	2.52	0.13	0.33	0.15	0.43	0.29	0.22	0.31
TiO ₂	2.39	2.38	2.00	1.89	1.94	7.66	8.19	6.72	7.27
Al ₂ O ₃	12.43	12.36	15.34	15.76	15.31	1.93	1.92	2.55	2.26
Cr ₂ O ₃	18.35	17.94	19.56	19.32	19.48	0.65	0.58	10.92	6.16
FeO	55.09	54.90	51.36	51.66	50.47	80.96	79.64	73.64	76.97
MnO	0.42	0.39	0.37	0.38	0.41	0.43	0.46	0.51	0.45
MgO	7.33	7.11	7.80	7.81	7.70	1.86	2.12	2.22	2.02
ZnO	0.17	0.12	0.00	0.01	0.06	0.27	0.34	0.29	0.35
Total	96.39	97.71	96.55	97.15	95.53	94.13	93.53	97.08	95.80

Note: 1a, b, in euhedral olivine; 2C-R, core to rim in phenocryst outside of olivine;
 3, GM, core and rim of phenocryst in groundmass; 4, core and rim of grain in
 olivine; 5, 6, grains in center of olivine phenocryst; 7, 8, groundmass opsesques;
 9, core and rim of large phenocryst in groundmass.

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APPENDIX I

OLIVINE

MK-15

	1I	2C	3	4R	5R	6C	7C	8I	9R	10R
SiO ₂	39.29	39.93	39.10	37.80	38.57	38.64	39.69	39.89	39.21	38.86
TiO ₂	0.00	0.00	0.01	0.01	0.04	0.02	0.00	0.00	0.00	0.01
FeO	17.77	17.25	17.30	21.22	22.14	18.04	17.65	18.29	18.32	19.34
MnO	0.27	0.21	0.24	0.37	0.41	0.27	0.24	0.29	0.30	0.31
MgO	43.23	43.93	42.24	40.00	39.45	42.20	42.86	43.09	42.33	41.42
CaO	0.19	0.19	0.14	0.20	0.21	0.16	0.16	0.21	0.20	0.22
Cr ₂ O ₃	0.01	0.00	0.00	0.04	0.02	0.02	0.01	0.02	0.02	0.00
Al ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.77	101.51	99.03	99.64	100.86	99.35	100.61	101.78	100.38	100.15
Si	0.993	0.997	1.003	0.985	0.994	0.992	1.001	0.998	0.997	0.995
Ti	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.375	0.360	0.371	0.462	0.477	0.387	0.373	0.382	0.389	0.414
Mn	0.005	0.004	0.004	0.007	0.008	0.005	0.004	0.006	0.006	0.005
Mg	1.627	1.634	1.615	1.554	1.516	1.616	1.613	1.607	1.604	1.582
Ca	0.004	0.004	0.003	0.005	0.005	0.003	0.003	0.005	0.005	0.005
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	3.004	3.000	2.995	3.013	3.000	3.005	2.995	2.998	3.000	3.001

Note: 1-4 euhedral phenocryst; 5 average of 4 rims; 7-9 core to rim of olivine xenocryst;
10R average of 3 rims in xenocryst.

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OLIVINES

ME-15 + 116

	ME-15		116
	XC	KR	
SiO ₂	40.22	40.35	35.21
TiO ₂	0.00	0.05	1.44
Al ₂ O ₃	0.09	0.08	0.29
FeO	17.57	18.51	29.97
MnO	0.34	0.33	0.38
MgO	43.07	41.94	32.72
CaO	0.27	0.28	0.28
TOTAL	101.56	101.54	100.29

C-3

APPENDIX K

THE GEOLOGY AND EVOLUTION OF THE CAYMAN TRENCH

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ABSTRACT

The geology and stratigraphic relationships of the Cayman Ridge, Nicaraguan Plateau and mid-Cayman spreading center, which have been determined from the succession of rocks recovered at 80 dredge stations in the Cayman Trench, are consistent with the inferred crustal structure of the region deduced from published geophysical data. The Cayman Ridge and Nicaraguan Plateau are composed of metamorphic, plutonic, volcanic, sedimentary and carbonate rock units that typically outcrop along continental margins and in island arcs. In contrast, the trench floor is composed of mafic and ultramafic rocks identical to those recovered from the major ocean basins.

Our petrographic, radiometric and paleontologic data is correlated with the regional geology of Central America and the Greater Antilles and suggests that the Cayman Ridge and Nicaraguan Plateau developed as a single, broad island arc during the Laramide Orogeny. By late-Eocene, volcanism had greatly diminished, uplift and erosion exposed the underlying igneous rock, thick clastic sequences were deposited in newly formed grabens and a zone of east-west axial accretion had been created between the rifted ridge and plateau. An average spreading rate of .4 cm/yr across the mid-Cayman spreading center since the Eocene accounts for approximately 200 km of left-lateral displacement between the Cayman Ridge and Nicaraguan Plateau. The geologic histories of the ridge and plateau differ slightly after the Eocene, but general subsidence, at an average rate of 6 cm/1000 yrs, caused progressive restriction of carbonate banks and reefs to a few isolated islands and algal pinnacles.

The pre-Cretaceous history of the Cayman Trench has been extrapolated from the Paleozoic - Mesozoic geology and structure of Central America and Cuba, while the Cretaceous to Recent evolution of the trench has been related to the relative motions between the North American, South American and Caribbean plates. Plate convergence during the Cretaceous caused southerly subduction of oceanic lithosphere beneath the ancestral Cayman Ridge - Nicaraguan Plateau, which subsequently led to the formation of a chain of volcanic islands to the south, along the North American - Caribbean plate boundary. Numerous ophiolite-like outcrops that fringe the north Caribbean margin are believed to reflect a Late Cretaceous closure of this subduction zone. Early Tertiary left-lateral shear and tensional stresses along this plate boundary split the Cayman Ridge from the Nicaraguan Plateau and a small spreading-center was created in the rift. Declining isotherms beneath the ridge and plateau caused general subsidence and local tectonic re-equilibration in the Late Tertiary.

Key words: Cayman Trench, Caribbean geology, spreading center, subsidence, radiometric ages, plate tectonics, petrology.

Appendix To

The Geology and Evolution of the

Cayman Trench

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TABLE #1

EASTERN CAYMAN TRENCH

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
1.	E435	19°28'N 75°36'W	4100	Meta-basalts, porphyritic with sodium enriched plagioclase phenocrysts and olive-green amphibole set in a fine grained crystalline matrix with minor chlorite, sericite and opaques, chlorite major alteration phase in many samples.
2.	E436	19°30'N 76°03'W	4000	Meta-basalts, greenschist, with relict plagioclase, and pyroxene altered to uraltite, chlorite and sericite, epidote and chlorite groundmass. Granodiorites, medium grained phaneritic with zoned plagioclase, amphibole, orthoclase, quartz, alteration minerals, chlorite, sericite and epidote, minor opaques. Metagranodiorites, low grade metamorphism, major plagioclase, quartz, hornblende, orthoclase, chlorite, minor epidote and opaques. Meta-igneous rocks, with major chlorite and relict plagioclase, minor quartz and opaques; Metadacite, porphyry with sericitized plagioclase and relict pyroxene altered to chlorite and epidote, embayed quartz set in fine matrix of plagioclase and chlorite, minor opaques; Meta-volcanics intensely altered to chlorite, epidote, with relict plagioclase; altered tonalite, w/plagioclase, quartz and opaques.
3.	E437	19°31'N 76°01'W	3400	Cataclastic and sheared granodiorites, with major rounded and broken fragments of quartz, plagioclase, orthoclase in a matrix of chlorite, epidote and fine pieces of plagioclase and quartz; Grade of metamorphism and cataclasis varies from minor to a granodiorite breccia composed of rounded and angular fragments of granodiorite, quartz, orthoclase, and plagioclase set in a matrix of chlorite and epidote, chlorite and epidote often in anastomizing veins or aggregates.
4.	E438	19°34'N 76°29'W	6600	Fresh granodiorite, medium grained, phaneritic, major plagioclase, quartz amphibole, orthoclase, chlorite, with minor epidote and opaques, amphibole altered to chlorite; K-Ar 83±2 M.Y. tonalite.
5.	E441	18°56'N 76°45'W	4250	Sheared fine-grained chlorite schist, with major chlorite, quartz, plagioclase and orthoclase, chlorite pseudomorphic after amphibole, minor opaques.
6.	E442	18°52'N 76°44'W	2425	Manganese plates and manganese encrusted limestone and coral.
7.	E443	18°50'N 76°43'W	2300	Manganese plates, 10 cm thick and large nodules, limestone in plates and serpentine fragment in one nodule; also recovered fragments of limestone and coral.
8.	E650	19°07.5'N 81°46.5'W	2196- 2075	Manganese coated sea-biscuit; organics.

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CAYMAN RIDGE

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
9.	21716	18°33.8'N 83°02'W	3950- 3100	Shallow water fossiliferous micritic limestone (Eocene-Oligocene); Deep water fossiliferous micritic limestone (Miocene); Dacite with embayed quartz phenocrysts, skeletal zoned plagioclase phenocrysts, biotite, chlorite and opaques in a fine granular felsic groundmass with microlites of plagioclase; Greenschist, with chlorite, epidote, and sparry calcite; Meta-volcanic with embayed quartz, sericitized plagioclase, sanidine biotite altered to muscovite and chlorite, minor opaques and apatite. Green shale; Red-green conglomeratic muds; Coquina. Rhyo-dacite with equal amounts of sanidine and zoned plagioclase, embayed quartz, in a microcrystalline groundmass of chlorite feldspar, quartz and opaques, accessory apatite.
10.	21721	18°46.5'N 83°08'W	1089- 890	Limestone; Deep and shallow water corals; Coquina; Sponges.
11.	21717	18°46.2'N 83°12.2'W	290- 52	Sea-biscuits; Algal balls and living corals.
12.	21718	18°47'N 83°12.1'W	56- 45	Algal limestone; Coralline limestone; Coquina; Algal balls; Sponges.
13.	21719	18°46'N 83°12.5'W	575- 162	Coquina; Coral and algal reefy limestone; Brittle stars; Sponges, Bored limestone; Pelecypod shells.
14.	21720	18°43.5'N 83°12.5'W	896- 792	Reefy limestone, siliceous spicules and sponges, living matter.
15.	21714	18°31'N 83°15'W	2416- 2377	Andesite (Keratophyre), sub-trachytic with phenocrysts of sodic plagioclase and green euhedral hornblende; lesser zeolites, opaques and chlorite; Amygduloidal dacite porphyry, plagioclase and hornblende phenocrysts in a fine felsic matrix with minor epidote, chlorite and opaques; Mudstone with secondary calcite veins; Fossiliferous micritic limestone (Plio-Pleistocene); Altered glassy volcanoclastic, contorted lenses of chlorite with epidote, plagioclase and sediment; Volcanic breccia containing pieces of keratophyre, quartz, greenschist volcanics.
16.	21713	18°31.9'N 83°23.7'W	1796- 1611	Mudstone with secondary sparry calcite; Red graywacke containing angular to subrounded fragments of plagioclase, hematite, ferruginous material, set in a red clay matrix; Fossiliferous calcarenite, containing micritic limestone clasts, shallow water fossils, plagioclase and epidote grains; Meta-basalt, porphyritic, spillite, phenocrysts of sodic plagioclase set in a granular matrix of epidote and chlorite with minor opaques; Arkosic breccia, rich in

CAYMAN RIDGE

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
				plagioclase with fragmental tuff, basalt porphries and secondary calcite; Micritic foraminiferal limestone (Plio-Pleistocene); Deep water corals; Calcareenite, well sorted, interbedded with calcilutite; Greenschist volcanoclastic with abundant granular epidote and fragments of plagioclase, fine grained volcanics, zeolites, tuff, sanidine; Calcareenites show various degrees of recrystallization.
17.	E651	18°32'N 83°27'W	3500- 3400	Lithic wacke with fragments of quartzite, metamorphic rocks, volcanics, sodium enriched plagioclase, hornblende, pyroxene and calcite, secondary quartz veins; Merocrystalline porphyritic basalt with glomerophenocrysts of plagioclase and pyroxene, epidote pseudomorphic after pyroxene, amygdules filled with penninite, feldspar and quartz; Mudstone; Meta-basalt with plagioclase phenocrysts in a micro-crystalline groundmass, relict pyroxene altered to epidote, plagioclase is sodium enriched; Sheared volcanoclastic, with fragments of tuff, chlorite, muscovite, epidote, clinozoisite, plagioclase, augite, amphibole; Meta-volcanics, with chlorite, epidote and devitrified glass. Pyroxene wacke; with abundant fresh euhedral to subhedral clinopyroxene in a matrix of quartz, chlorite and clay, minor glauconite, foraminifera, opaques, mudstone, volcanics, oxidation of opaques is common; shallow water foraminiferal limestone (Mid Eocene).
18.	E653	18°21'N 83°27'W	5000- 4650	Greenschist metamorphics, with major chlorite and/or epidote, variable amounts of quartz, plagioclase, limonite and opaques; Mica schist with muscovite and chlorite, minor quartz, limonite and opaques; Gneiss, quartzo-feldspathic, with chlorite, limonite, granular opaques; Dacite composed of acicular to tabular phenocrysts of plagioclase in columnar or radial aggregates, quartz, potassium feldspar, minor chlorite, apatite and opaques; Siltstone predominantly of limonite clay with minor quartz and plagioclase; Lithic graywacke with fragments of tuff, schist, gneiss, volcanics, clay, quartz, plagioclase, opaques in a clay and chlorite matrix. Metagabbro composed of altered plagioclase, chlorite and penninite replacement of mafic minerals, scattered opaques.
19.	21708	18°26'N 83°27.8'W	1528- 1350	Basalt, with clinopyroxene, plagioclase and serpentized olivine phenocrysts in a micro-crystalline groundmass of plagioclase epidote, chlorite and calcite; Deeply weathered breccia with fragments of mudstone and basalt in a fine grained marly matrix; Mn-nodules and encrustaceans, siliceous corals, pteropods and bryozoans. Silty arenite with convolute bedding, epidote rich and opaque layers, frag-

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CAYMAN RIDGE

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
				ments of plagioclase and basalt, clay cement with minor calcite and ferruginous matter
20.	21711	18°30'N 83°31'W	1640- 1590	Metavolcanic (Keratophyre), with fragments of subhedral to anhedral sodic plagioclase, finely disseminated calcite, epidote, talc with minor opaques and ferruginous material in bands, microlitic groundmass; Amigdoloidal metavolcanic, with abundant epidote and chlorite, amygdules filled with calcite and chlorite, trachytic fabric is evident. Fossiliferous micritic limestone, (Plio-Pleistocene); Meta-Andesite with chloritized plagioclase phenocrysts, epidote and penninite replacement of matrix, in contact with manganese covered recrystallized limestone containing basaltic fragments, partially phosphatized.
21.	21709	18°27.5'N 83°35'W	2150- 1840	Mustone; Limestone (Miocene); Micritic Limestone (Plio-Pleistocene); Calcareous mudstone with opaque layers, scattered mineral grains and sulphides, most are Mn encrusted.
22.	21710	18°26.8'N 83°35'W	3200- 2750	Tuffaceous volcaniclastic lapilli tuff composed of drop-like glass particles surrounded by a brown alteration mineral, the groundmass is glassy and microlitic, folding is evident; Mica schist, composed of platy micaceous minerals surrounding larger fragments of plagioclase and opaques, veins of calcite and epidote, also inter-granular quartz and epidote; Fossiliferous micritic limestone (Plio-Pleistocene); Cataclastic gneiss with granular quartz and plagioclase, biotite, penninite, interstitial opaques, secondary carbonate, possible sheared plutonics.
23.	21722	18°17'N 83°45'W	2410- 1800	Marble, recrystallized algal limestone with macrofossils, (shallow water); Lithic tuff containing pieces of subhedral plagioclase, andesite (lateratized), limestone, lithic arenite, basalt, volcanics, minor opaques (oxidized), and veins of chlorite and talc, matrix varies from microcrystalline trachytic to glassy; meta-volcanic consisting of lath shaped plagioclase phenocrysts and radial aggregates of epidote and clinozoisite in a microcrystalline felsophyric matrix, minor chlorite, calcite, sericite and opaques; Weathered conglomerate with quartz, tuff, limestone, granitic plutonics, arenite, in a calcareous cement; Adamellite composed of equal amounts of plagioclase and orthoclase, quartz, with minor chlorite, epidote, clinozoisite

CAYMAN RIDGE

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
				altering mafics, and clay weathering products; Various volcanics some of which have undergone greenschist metamorphism, vitric to felsophyric, often trachytic, plagioclase phenocrysts, mafics altered to chlorite and/or epidote, opaques often oxidized; Sub-arkose, major plagioclase, orthoclase and quartz, bands of opaques, minor calcite (fossils), volcanics, ferruginous material and opaques; Fossiliferous micritic limestone with Eocene-Miocene shallow water and pelagic forams.
24.	21724	18°19.5'N 83°47.6'W	4700- 2000	Vesicular meta-basalt, vitrophyric with divergent acicular and columnar sodium enriched plagioclase, epidote, chlorite and finely disseminated oxidized opaques set in a devitrified glassy groundmass, vesicles filled with chlorite, fine opaques, and calcite; Conglomerate with clasts of tuff, limestone, granitic plutonics, volcanics, meta-basalt, graywacke, red arenite, in a calcite cement; Volcanic breccia, angular fragments of plagioclase, quartz, orthoclase, various vitrophyric volcanics that are often trachytic and greenschist, minor epidote, sulfides, and chlorite, opaques commonly oxidized, clay and secondary calcite cement; Andesite porphyry, columnar and glomerophenocrysts of plagioclase in a granular xenomorphic groundmass of plagioclase, orthoclase and quartz, with minor chlorite and opaques; Welded red tuff, with sub-to euhedral plagioclase, phenocrystic and polycrystalline quartz, abundant calcite veining, minor embayed quartz, volcanic fragments, apatite, finely disseminated oxidized opaques; Water laid tuff with abundant opaques, calcite veinlets, trace microfossils, plagioclase microlites, in a cryptocrystalline shardy groundmass.
25.	21726	18°21'N 83°45'W	2600- 2055	Manganese encrusted limestone; Red volcanic breccia containing abundant angular fragments of volcanics, welded tuff, plagioclase, minor quartz, calcite, arkose, wacke, granitic plutonics, red-black opaque rich clay matrix; Dacite subtrachytic with phenocrysts of plagioclase and quartz with minor amounts of biotite, chlorite, orthoclase, penninite, apatite and opaques, extensive chlorite alteration of felsophyric groundmass common; Sub-arkose, predominantly consisting of sodic plagioclase with less amounts of volcanics, chlorite, and opaques in a siliceous calcareous cement; Extremely weathered volcanics and/or siltstone.
26.	E657	18°24'N 84°02.5'W	1100- 800	(Recent) limestone and coral; Iron stained fossiliferous shallow water limestone with abundant opaques and calcite grains (Miocene).

CAYMAN RIDGE

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
27.	E659	18°17.4'N 84°02.8'W	2300- 1985	Fossiliferous micritic limestone (Miocene); foraminiferal chalk (Early Miocene); fossiliferous tuff (Mid Miocene).
28.	E663	18°15.5'N 84°04.8'W	4800- 4200	Meta-volcanic, with acicular and tabular plagioclase relicts and abundant chlorite and fine granular epidote.
29.	E660	18°20.5'N 84°05.6'W	3200- 3000	Medium grained meta-dolerite, altered plagioclase, calcite replacement, and chloritization of mafics, minor opaques and ferruginous material. Volcanic wacke composed of fragments of tuff, quartz, plagioclase, chlorite, volcanics, penninite and epidote, shows bedding; Tuffaceous silty mudstone, with abundant opaques and polycrystalline quartz, possibly chert nodules, bedding evident.
30.	21728	18°17.5'N 84°25'W	1500- 1400	Semi-consolidated ooze; Fossiliferous limestone (Plio-Pleistocene).
31.	E1105	18°21'N 84°33.6'W	2000- 1600	(Miocene) marl and chalk, massive with manganese crust.
32.	E1091	18°06'N 84°51'W	3070- 2950	Granodiorite composed of phaneritic plagioclase, orthoclase, quartz, hornblende and apatite, minor epidote, monazite, biotite, and opaques, 64±10 M.Y.; Meta-granodiorite with sericitized deformed plagioclase laths, biotite and hornblende altered to penninite and epidote, accessory apatite, opaques, secondary calcite; Mudstone; (Pleistocene) ooze; manganese crust. Granodiorite, very fresh, 59.1 ± 3.7 m.y.
33.	E1093	18°07.2'N 84°51.5'W	1770- 1000	Manganese encrusted fossiliferous indurated siliceous oozes; two inch thick manganese crust; Light brown ooze, (Eocene-Oligocene); Indurated phosphatized calcareous ooze, (Miocene); Fossiliferous limestone, (Eocene-Miocene), shallow water, Late Pliocene (deep water).
34.	E1092	18°10'N 84°53'W	2540- 2190	Friable tan fossiliferous calcarenite with Recent forams; Recent fauna.
35.	E1094	18°07'N 84°53'W	1612- 1225	Manganese encrusted indurated light brown ooze, (Pleistocene); Recent corals and sponges.
36.	E1095	18°09'N 84°54'W	2490- 2126	Manganese encrusted ooze; siliceous sponges.

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered	CAYMAN RIDGE
37.	E1096	18°05.5'N 84°53.8'W	3050- 2620	Granodiorite, consisting of major plagioclase, orthoclase, quartz, hornblende, minor biotite and opaques, Meta-granodiorite with sericitized and saussuritized plagioclase and orthoclase, quartz, chlorite, minor opaques; Adamellite with equal amounts of quartz, plagioclase and orthoclase, minor biotite, chlorite and opaques. Phosphatized calcareous breccia with Plio-Pleistocene planktonic forams, manganese encrusted; Tremolite-actinolite schist with variable amounts of chlorite, biotite, muscovite, quartz, feldspar and opaques; Anthophyllite schist with minor tremolite, quartz, albite and opaques; hand specimens show planar linear fabric and compositional banding. Granodiorite 59.8 ± 1.3 m.y.	
38.	E1097	18°06'N 84°54.5'W	2300- 1780	Fossiliferous micritic limestone, shallow water (Miocene) fossils, indurated and manganese encrusted. Phosphatized indurated limestone, (Eocene-Oligocene), shallow water, Orbitoidal limestone (Late Oligocene) carbonate shelf or bank.	
39.	E1098	18°04.5'N 84°52'W	3287- 2350	Granodiorite, with major plagioclase, orthoclase, hornblende (replaced by chlorite), quartz, minor apatite and opaques, 59 ± 3 M.Y.; Grandiorite ranges from fresh to deeply altered with abundant sericite, chlorite and apatite; Manganese encrusted limestone (Miocene); phosphatized.	
40.	E1099	18°04'N 84°52'W	4500- 3700	Granodiorite, with zoned plagioclase, orthoclase, quartz, hornblende altered to biotite and chlorite, minor apatite, opaques and zircon, 60 ± 2 M.Y.; Alteration of granodiorites common, plagioclase to sericite, orthoclase to kaolinite, mafics to penninite and chlorite; Chlorite schist, composed of platy chlorite after amphibole in a microcrystalline groundmass of quartz, albite, and opaques; Gneiss composed of quartz, plagioclase, orthoclase, epidote, apatite, clinozoisite, in a platy fine matrix of chlorite and biotite. Gneiss interbedded with schists or banded, often contain significant amounts of hematite; Tremolite-actinolite, biotite schist with minor epidote, apatite, quartz, albite and opaques 69 ± 9 M.Y.; Meta-granodiorites, blastoporphritic with zoned skeletal plagioclase in a xenomorphic granular matrix of quartz, feldspar, biotite, sphene, chlorite, apatite, zircon and opaques; Red mudstone; Manganese encrustations; Oligocene-Miocene neritic limestone.	

CAYMAN RIDGE

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
41	E1104	18°01.5'N 85°01.5'W	4256- 3600	Fossiliferous calcarenite, (Eocene-Oligocene); Altered plutonic, possibly a granodiorite with plagioclase, kaolinitized orthoclase, minor opaques, apatite, extensive chlorite and calcite replacement; Volcanics (Dacite-Andesite), sericitized phenocrysts of plagioclase and some with embayed phenocrysts of quartz in a vitrophyric chloritized groundmass, minor epidote, relict hornblende and opaques; Altered red volcanics with relict plagioclase, polycrystalline quartz, limonite and hematite in a fine micaceous groundmass. Greenschist volcanoclastics often highly oxidized, foraminiferal limestone (Late Paleocene).
42.	E1100	17°57.8'N 85°27.5'W	3250- 2891	Silicified and phosphatized limestone with manganese crust and dendrites (Miocene); Calcareous breccia containing fragments of limestone, red tuffs and volcanics, plagioclase, quartz and fossil fragments (Oligocene); Vitrophyric volcanics, containing embayed quartz, subhedral sodium enriched plagioclase, hornblende, orthoclase, limonite, hematite, magnetite and epidote in a matrix of polycrystalline quartz, plagioclase microlites and altered glass; Crystal tuff, with major embayed quartz, minor chlorite, zeolites, relict amphibole with opaque coronas, feldspars are subtrachytic in a perlitic matrix; Red metabasalt with euhedral to subhedral phenocrysts of sodium enriched plagioclase, subhedral to anhedral clinopyroxene, epidote, clinozoisite, opaques, minor zeolites, orthopyroxene, olivine (iddingsite), penninite, in a microcrystalline microlitic groundmass containing finely disseminated magnetite and hematite; Meta-volcanic (greenschist) composed predominantly of euhedral to subhedral granular and radial epidote and polycrystalline quartz with minor embayed quartz, piedmontite, plagioclase and relict pyroxene, with accessory apatite, hematite, and chlorite, hand specimens show successive lava flows, many of the volcanics are opaque rich; Marble in contact with quartzite, (Recent) limestone.
43.	E1101	17°55.5'N 85°27'W	2645- 2265	Silicified limestone; Shallow water limestone breccia; Volcanoclastic (crystal tuff) with phenocrysts of subhedral fractured sodium enriched plagioclase and embayed quartz, relict hornblende and pyroxene, being altered to chlorite and opaques, minor tuffaceous fragments, and opaques in a groundmass of plagioclase, fine opaques, polycrystalline quartz and altered glass; Red volcanic (Dacite) with high percentage of opaque alteration coronas and finely disseminated hematite in groundmass, plagioclase phenocrysts, embayed quartz, minor epidote, piedmontite, apatite, hornblende in a crypto-crystalline glassy groundmass; Flow evident in hand specimen and thin section; Orbitoidal limestone (Late Cretaceous), shallow shelf or bank.

NICARAGUAN PLATEAU

No.	Dredge No.	Position	Depth (f)	Rock Types Recovered
44.	E1071	18°01'N 79°07.8'W	1763- 1472	Red-brown arenites and conglomerates; Red lithic arenites composed of fine grained, well sorted fragments of plagioclase and quartz with minor glauconite, calcite, serpentine; Lithic conglomerate composed of rounded to subrounded fragments of andesite, basalt, limestone, euhedral grains of plagioclase and augite, minor fragments of quartz, clay and calcite, ferruginous and secondary calcite cement; Limestone; Arenites are often friable and bedded.
45.	E1072	18°02'N 79°11'W	2994- 2515	Semi-consolidated Globigerina ooze (Pliocene-Recent).
46.	E1073	17°54'N 79°50'W	3300- 2700	Arenites, semiconsolidated, friable with variable carbonate content; Marly limestone; Micritic limestone with burrowing evident.
47.	E1078	17°45.5'N 80°58'W	2990- 2155	Siltstones, limestone, arenites and consolidated ooze with forams and pteropods of (Pliocene-Pleistocene) age. Calcarenite with fragments of plagioclase, quartz, epidote and opaques; Water laid tuff containing plagioclase, quartz, chlorite, chert, recrystallized forams and opaques.
48.	E1079	17°48'N 80°54.2'W	3680- 3100	Argillite with evidence of convolute bedding and flowage; Consolidated ooze; Greenschist volcanic with uralitized pyroxene, zoned plagioclase laths and aligned chlorite and epidote in a fine matrix of polycrystalline quartz and feldspar; Interbedded and graded argillites and arenites with variable carbonate contents; Biopelmicrite, partially recrystallized; Calcilutite.
49.	E1080	17°45.2'N 81°W	3400- 3240	Partially altered andesites with euhedral plagioclase (replaced by sericite) and augite set in a fine grained matrix of microlites and/or glass being altered to chlorite, plagioclase is glomeroporphyritic, minor zeolites, clinozoisite and opaques, extensive secondary quartz, epidote and calcite veins; Some are amygdoloidal.
50.	E1081	17°45.3'N 80°59'W	2621- 2598	Fossiliferous micritic limestone; Greenschist volcanics with embayed quartz phenocrysts, replaced and altered plagioclase and pyroxene, very fine matrix of microlites and altered glass; Volcanics (Andesite-Dacite) with minor phenocrysts of plagioclase, quartz and pyroxene, red altered bands of opaques common, flow textures in hand specimens, Sheared tuffaceous volcanoclastic breccia with fragments of calcilutite and volcanics; Secondary sulphides as a minor phase.

NICARAGUAN PLATEAU

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
51.	E1082	17°47'N 80°59'W	2500- 2390	Small fragments of volcanics and limestone.
52.	E1083	17°47'N 80°56'W	2506- 1900	Fossiliferous micritic limestone; Consolidated ooze, bioturbated; Quartz arenite composed predominantly of fine angular quartz in a secondary sparry calcite cement with lesser fragments of plagioclase, uralite and opaques; Laminated semiconsolidated siltstone with calcite cement; some cherty zones; Limestone nodules, with centers silicified, chalky marl (Late Oligocene) deep water.
53.	E1085	17°30'N 83°00.5'W	4000- 3725	Fossiliferous micritic limestone; Arenites with angular well sorted quartz, orthoclase, plagioclase, and minor chlorite, opaques, fossils, glauconite and volcanics all cemented by calcite and silica; Calclithite, with mineral grains and fragments of limestone, wacke, shells and fecal pellets; Breccia with plagioclase, orthoclase, quartz, microcline, tuff, basalt, arenite, minor chlorite, perovskite, opaques in a secondary calcite cement; Bioclastic (Oligocene) limestone; Laminated graywacke with fragments of minerals, volcanics, shells and microfossils; Argillite.
54.	E1086	17°29.8'N 83°05'W	5000- 4000	Interbedded siltstone and calcilutites, with fossiliferous calcareous fragments interbedded with silt and clay size grains; Turbidite-type rocks: Litharenites, Graywackes, Red lithic graywacke; Microbreccia; many of the rocks have significant percent carbonate particles and cement. Sedimentary rocks generally contain granitic and metamorphic detritus; Red wacke with fragments of plagioclase, quartz volcanics, mica schist, quartzite, opaques in a red clay and carbonate matrix.
55.	E1087	17°30.5'N 83°07.3'W	5500- 4900	Red feldspathic graywacke, showing convolute bedding and poor sorting of angular mineral grains of predominantly hematite and plagioclase with minor chlorite, quartz, calcite, clay fragments, orthoclase, muscovite and volcanics; Conglomerate containing pieces of mica schist, limestone, quartz, microcline, uralite, plagioclase, graywacke, chlorite schist and opaques in a microcrystalline matrix of quartz and feldspar; Lithic tuffs with angular fragments of quartz, plagioclase, calcite, talc, graywacke, glass shards, orthoclase and minor chlorite, uralite, epidote, perovskite, penninite, fossils and opaques in an altered matrix of glass and chlorite, often veined with secondary calcite with minor barite; Wackes and breccia with extensive red weathering. Breccia contains fragments of schist, granitic rock,

NICARAGUAN PLATEAU

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
				calcite, polycrystalline quartz; Metasediments: arenites and argillites with linear fabric; shearing and recrystallization of matrix. Many of these appear to be turbidites.
56.	E698	17°26.4'N 83°12'W	5423- 5267	Graywacke with angular unsorted grains of quartz, plagioclase, orthoclase and minor muscovite and opaques set in a fine matrix of clay, mica and quartz, some graywackes show convolute bedding while others are finely laminated; Quartzose arenite with minor fossils (recrystallized), plagioclase, volcanics and opaques; Quartzite, composed of fragmental recrystallized quartz in a polycrystalline quartz groundmass with minor bands of opaques; Limestone with minor pieces of graywacke; Bedded graywacke with quartz, volcanics, plagioclase, muscovite in a calcareous cement.
57.	E699	17°24'N 83°14'W	4500- 4400	Bedded lithic graywacke, with angular unsorted fragments of quartz, plagioclase, orthoclase and quartzite, minor volcanics, muscovite, and opaques in a marly calcareous cement; Graywacke with angular quartz, plagioclase, orthoclase, muscovite and opaques set in a clay rich matrix; Fossiliferous graywacke (Eocene-shallow water); Calcareenite; Calcilithite; Calcareous conglomerate (Oligocene) minor quartz, orthoclase and plagioclase; Quartz arenite with microcline, quartz, muscovite, and plagioclase.
58.	E700	16°52.8'N 82°52.8'W	1642- 1400	Miocene and Pliocene semiconsolidated ooze and marl.
59.	E1088	17°34.1'N 83°39.5'W	5300- 4850	Recrystallized fossiliferous limestone, with minor opaques and quartz (L.K.); Fossiliferous calcilutites with minor opaques and quartz; Tuff with mineral, rock, calcite and fossil fragments; Micritic limestone with fossils and minor quartz, feldspar, tuff and opaques; Interbedded calcilutites and calcarenites that show the effects of bioturbation, fine grained laminated limestone (Early Miocene). Cataclasis evident in some samples.
60.	E695	17°29.1'N 83°44'W	3400- 3050	Calcareenite, with minor fragments of quartz, glass shards, plagioclase and fossils; some calcarenites show bedding, and significant amount of glass shards; Recrystallized fossiliferous limestone with minor quartz, plagioclase and opaques (Plio-Pleisto). Limestone, foraminiferal, deep water (Early Miocene); Laminated limestone (Late Oligocene) deep open sea; laminated fossiliferous tuff (Early to Mid Miocene); laminated tuffs.

NICARAGUAN PLATEAU

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
61.	E696	17°29.5'N 83°43'W	3400- 3300	Calcarenites; Fossiliferous limestone, deep ocean-sea (Early Miocene); Fragmental limestone, Neogene (probably Oligocene-Miocene) deep open sea.
62.	E697	17°27'N 83°43'W	2250- 2000	Fossiliferous micritic limestone (Pliocene-Recent); partially recrystallized; Calcarenite, with prominent graded bedding (Neogene); Foraminiferal limestone (Early Miocene), deep open sea.
63.	E1090	17°13.5'N 84°51'W	3500- 3430	Poorly sorted graywacke; Arenites interbedded with argillites that show graded poor bedding; Laminated argillites, semiconsolidated, friable argillaceous tuff; Sediments appear to be turbidites and contain microfossils, of Oligocene age.

MID-CAYMAN SPREADING CENTER

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
65.	E642	19°08'N 79°09.6'W	6900- 6500	Serpentinized peridotite with anhedral fragments of bronzite, magnetite and talc.
66.	E643	19°13'N 79°11.9'W	7100- 6800	Serpentinite.
67.	E644	19°01.9'N 80°12.7'W	7157- 7000	Graywacke, finely bedded, ferruginous, composed of angular fragments of plagioclase, muscovite, serpentine, pyroxene and quartz in a clay matrix; Various serpentinites commonly with magnetite, talc, bronzite and relict clinopyroxene which may show cataclastic and sheared textures; Serpentinized peridotites, with fresh and relict clinopyroxene, spinel, penninite, orthopyroxene and minor amphibole, perovskite, magnetite and talc, (after olivine).
68.	E645	19°01.5'N 80°07'W	5880- 5600	Serpentinites, with relict pyroxenes and scattered magnetite and opaques; Serpentinized peridotite; Holocrystalline basalt composed of phenocrysts of plagioclase and pyroxene set in a groundmass of plagioclase and pyroxene, with minor actinolite-hornblende, mica? talc (after olivine) as alteration products, minor opaques.
69.	E646	19°10.9'N 80°19.6'W	6350- 6200	Weathered manganese encrusted basalts; Merocrystalline porphyritic amygduloidal basalt with lath and tabular shaped phenocrysts of plagioclase set in a fine grained groundmass of acilic plagioclase and granular pyroxene, minor iddingsite pseudomorphs after olivine, amydules filled with secondary minerals, opaque rich matrix ; plagioclase is zoned and may enclose spinel fragments.
70.	21697	18°N 80°27'W	4500- 4470	Small fragments of volcanic rock.
71.	21698	18°05.5'N 80°24'W	2875- 2775	Meta-dolerite, greenschist, subophitic contains sodium enriched plagioclase phenocrysts in a medium grained groundmass of plagioclase and clinopyroxene altered to uralite and chlorite, plagioclase saussuritized, also interstitial chlorite, epidote and clinozoisite, minor opaques; Vitrophyric basalt, with phenocrysts of plagioclase, and diallage in a glassy matrix with granular augite and plagioclase microlites, minor chlorite; Dolerites exhibit chilled outer margins. Gabbro with predominant anhedral plagioclase, lesser intergranular diallage and iddingsite pseudomorphs after olivine, alteration of pyroxene to hornblende, exsolution lamellae and deformation lamellae common; Cataclastic serpentine breccia composed of fragments of fibrous serpentine in an anastomizing matrix of talc and carbonate, opaques

MID-CAYMAN SPREADING CENTER

No.	Dredge No.	Position	Depth (m)	Rock Types Recovered
				common; Tremolite-actinolite amphibolite with muscovite, chlorite, talc, epidote and opaques; Greenschist meta-sediments, containing muscovite, chlorite, talc, epidote, quartz, feldspar and some variable amounts of calcite, they exhibit folding, shearing and some are porphyroblastic.
72.	21699	18°14.5'N 80°10.4'W	4000- 2946	Fossiliferous micritic limestone (Pliocene); Breccia, greenschist, cataclastic with predominant epidote and clinozoisite, with basalt and mudstone fragments; Meta-dolerite, subophitic, greenschist composed of saussuritized plagioclase and granular augite with minor opaques, chlorite, amphibole and epidote, Gabbro composed of sodium enriched plagioclase, clinopyroxene and iddingsite pseudomorphic after olivine, minor opaques, intersertal chlorite and alteration products, deformation lamellae and cataclasis evident; Serpentinized peridotite with relict fragments of olivine and pyroxene, elongate veins of magnetite within sheared serpentine; Meta-basalt composed of sodium enriched plagioclase and granular clinopyroxene in a microcrystalline groundmass of chlorite, epidote, clinozoisite and devitrified glass, minor opaques.
73.	21700	18°17.9'N 80°03.2'W	3059- 2550	Fossiliferous micritic limestone (Miocene), partially recrystallized tests and minor detrital fragments; Weathered basalt composed of variolitic aggregates of plagioclase, granular clinopyroxenes, alteration products after olivine; and minor opaques in a cryptocrystalline groundmass; Sub-ophitic dolerite, with sodium enriched plagioclase, granular clinopyroxene and brown-gold alteration (chlorophaeite) products, some pseudomorphs of olivine.
74.	E1074	17°54'N 80°34'W	3900- 3200	Serpentinites: Serpentinized limestone with marble-like texture, recrystallized calcite with veins of serpentine and associated magnetite; Subophitic serpentinized dolerite composed of major plagioclase and clinopyroxene and serpentine pseudomorphic after olivine, minor opaques, zeolite and interstitial serpentine; Serpentinized peridotite with scattered pyroxenes and opaques, minor sphene.
75.	21702	18°N 81°35'W	3060- 2500	Altered vitrophyric volcanic (basalt) predominantly composed of devitrified glass with relict plagioclase and pyroxene with minor opaques; Cataclastic meta-gabbro with strained plagioclase, diagenetic pyroxenes altered to chlorite and urallite, minor amphibole and opaques; Basalt, with variolitic texture, granular interstitial pyroxene and minor opaques; Olivine meta-gabbro, with pyroxene-magnetite coronas surrounding olivine, plagioclase fractured and strained, variable clino-and

No. Dredge No.	Position	Depth (m)	Rock Types Recovered
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MID-CAYMAN SPREADING CENTER

orthopyroxene contents, minor serpentine, talc, calcite, actinolite and chlorite veins; Medium grained recrystallized plagioclase gabbro, mafics all replaced by uralite and chlorite; Marly limestone, containing Miocene-Pliocene fossil fragments, angular fragments of plagioclase pyroxene; Anorthositic rocks often in contact with gabbros, high percentage of plagioclase (75%) with minor chlorite, epidote and opaques (replacing original mafics). Pyroxene gabbro, with abundant (75%) euhedral pyroxene with intercumulus plagioclase

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|-----|-------|----------------------|---------------|--|
| 76. | 21703 | 18°04'N
81°40'W | 4313-
4100 | Serpentinized with minor relict pyroxene and opaques; Talc rock with minor opaques. |
| 77. | 21704 | 18°30'N
81°57'W | 3800-
2340 | Foram ooze. |
| 78. | 21705 | 17°55'N
81°53'W | 5225-
4800 | Fine grained vesicular basalts with augite phenocrysts and variolitic plagioclase phenocrysts in a matrix of skeletal plagioclase and olivine with granular clinopyroxene and minor opaques; Calcareous breccias, with basalt fragments. |
| 79. | 21706 | 18°09'N
81°42.5'W | 2420 | Fine grained vesicular basalt, highly weathered; Fossiliferous limestone. |
| 80. | E1084 | 17°56'N
81°56.3'W | 2435-
2300 | Cataclastic meta-gabbros with coarse crystals of diagenesis and plagioclase, minor chlorite and serpentine; Serpentinized gabbro; Consolidated ooze. |

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INTRODUCTION

After more than a century of continuous investigation, the earth's crust beneath the Caribbean Sea still possesses numerous unsolved problems concerning its genesis, structure, and geological history. Its morphology, seismic structure, gravity field and sediment stratigraphy are fairly well known. A program of direct sampling of sea floor escarpments, initiated by one of us (B.C.H.) in 1966, has provided important evidence concerning the composition and age of the Beata and Aves Ridges, Eastern Antilles Arc, Puerto Rico Trench, Bahama and Blake Escarpments, Yucatan Slope, and Cayman Trench. In most reconstructions of the geologic history of the Caribbean, the Cayman Trench plays a crucial role, yet few constraints have been placed on its age or mode of formation. All too often, the trench is used as a "zone of convenience" where lithospheric plates couple, decouple, subduct or slide past one another, with little concrete evidence to substantiate these motions.

Geophysical measurements indicate that the Cayman Trench is an anomalous region compared to the continents and major ocean basins (Ewing, Antoine and Ewing, 1960; Bowin, 1968; Ericson and others, 1972). In order to unravel the complexities and resolve the geological ambiguity of this region, direct sampling of the crust was required. This work was accomplished on Duke University's R.V. EASTWARD from which 80 dredge hauls from the Cayman Trench were successfully recovered during 1971, 1972, and 1973 (Fig. 2). From these, the composition and age of rock units outcropping in the trench have been determined. The combination of this new information with previously obtained

geophysical data leads to a new structural and evolutionary model for the region.

The Cayman Trench is a seismically active submarine depression in the Caribbean crust which extends 1,600 km from the Windward Passage (between Cuba and Hispaniola) to the Gulf of Honduras (Fig. 1.). The 120-180 km wide graben-like trough is bounded on the north by the Cayman Ridge and by the Nicaraguan Plateau to the south. The asymmetrical Cayman Ridge extends from the Sierra Maestra of Cuba to within 100 km of the base of the British Honduras continental slope where it disappears beneath thick sediment cover in the Yucatan Basin. Its northern flank slopes gently beneath the Yucatan Abyssal Plain while the precipitous southern escarpment drops abruptly to the trench floor. The Cayman Islands, Misteriosa and Rosario Banks, and some isolated algal reefs lie near or above sea level on top of the ridge (Fig. 2.).

Seismic reflection profiles show the steep north wall of the trench to be virtually sediment free while isolated ponds of sediment lie between peaks on top of the ridge (Fig. 3). Seismic profiles across the western end of the ridge suggest that it is an uplifted fault block with scarps between 30° and 40° and minor sediment deformation (Falquist and Davies, 1971; Dillon and others, 1972; Malin and Dillon 1973). Dillon and Vedder (1973) have suggested that the western Cayman Ridge is a rifted and rotated continental fragment of British Honduras. East of the Cayman Islands toward the Sierra Maestra, the Ridge is less steep and progressively more sediment covered.

The broad Nicaraguan Plateau, extending from Honduras and Nicaragua to southwest Haiti, descends gently southward through a series of steps, disappearing beneath the sediments of the Columbia Basin and dips steeply northward to form the south wall of the Cayman Trench. Swan Island and the Bay Islands lie on a series of elongated ridges known collectively as the Bonacca Ridge which forms the western most section of the southern wall. Bonacca and Swan deep (5000m) lie at the base of the scarp. Much of the southern wall of the trench has an irregular, blocky and discontinuous appearance as compared to the steep regular topography of the north wall (Pinet, 1975)

Between 80°W and 84°W a series of linear, steep, north-south trending ridges and deep basins transect the trench floor. The N-S ridge and basin topography is symmetrically divided by a 5,000-6,000 m deep V-shaped north-south valley at approximately $81^{\circ}40'$. This axial valley connects the east-west deeps lying at the base of the northeast wall with those at the base of the southwest wall.

Seismic reflection, bathymetric, magnetic data led Holcombe and others (1973) to propose the existence of a mid-Cayman spreading center at this axial valley. Sediment thickness, morphology, magnetic, gravity, heat flow and seismic data all support this hypothesis. The N-S axial ridges are extremely rough, virtually free of sediment and have steep slopes that are very suitable for dredging.

Seismic reflection profiles show that sediments are thin or absent in the central ridges with small ($<200\text{m}$ thick) pockets of flat lying sediments in the valleys (Fig. 3) (Ewing and others, 1960; Edgar and others, 1971; Ericson and others, 1972).

Sediment accumulation increases progressively to the east and to the west. West of Swan Island, basement is obscured by the great influx of terrigenous sediments from the continental margin. South of Cuba the sediment also thickens but steep basement ridges protrude the cover making dredging possible.

Seismic activity is generally confined to the southwest and northeast walls joined by an active zone corresponding to the axial rift valley (Sykes and Ewing, 1965). Assuming the mid-Cayman spreading center is a zone of axial accretion, the linear deeps in the northeast and southwest are transform faults (Oriente and Swan fracture zones respectively). In detail, shallow focus epicenters are somewhat scattered in a zone 50 km wide along the fracture zones and rift valley. Seismicity is also high where the mid-Cayman spreading center intersects the walls of the trench and where surrounding topographic features extend into the trench (Holcombe and others, 1973.).

First motion studies (Molnar and Sykes, 1969) indicate predominantly left lateral strike-slip movement along the walls of the trench, with lesser amounts of normal faulting. The present boundary between the eastward moving Caribbean Plate and the westward moving North America Plate is defined by a nearly continuous zone of seismic activity in the trench. Estimated relative rates of east-west movement along this plate boundary vary from around 0.5 cm/yr (Malfait and Dinkleman, 1972; Pinet, 1972) to over 2 cm/yr (Molnar and Sykes, 1969, Holcombe and others, 1973, Jordan, 1975).

Heat flow is highest near the mid-Cayman spreading center and Oriente and Swan fracture zones. Mean heat flow in the Cayman Trench is 2.01 HFU which is significantly higher than the 1.46 ± 0.19 and 1.38 ± 0.11 HFU measured in the Yucatan Basin and Cayman Ridge respectively (Ericson and others, 1971). This value (2.01) is much higher than the world-side average of 1.50 HFU but near the value for the active spreading segments of the mid-ocean ridge (Langseth and von Herzen, 1972). A positive Bouguer gravity anomaly diminishes to the east and west along the trench. Bowin (1968) noted that it does not extend across the Windward Passage to the Puerto Rico Trench, but continues into the Enriquillo Basin-Cul de Sac Trough in Hispaniola. Although the floor of the Cayman Trench is in isostatic equilibrium, Bouguer values are slightly lower over the mid-Cayman spreading center and free air anomaly values are slightly negative suggesting a low density root compatible with spreading center. Negative free air values were recorded over the eastern end of the trench. Bouguer lows have been recorded over the Cayman Ridge and Misteriosa Bank and anomaly values decrease westward along the Nicaraguan Plateau (Bowin, 1968; 1976).

The Cayman Trench is generally magnetically quiet, and is characterized by low amplitude (+100 to -150) non-linear anomalies that appear to correlate with irregular topographic highs and lows (Banks and Richards, 1969; Gough and Heirtzler, 1969; Ericson and others, 1972). Recent work suggests that symmetrical magnetic lineations form a pattern parallel to the ridges of the mid-Cayman spreading center (Mathews, 1974). A 300 gamma

asymmetric positive magnetic anomaly has been recorded on the south slope of the western-most Cayman Ridge (Fahlquist and Davies, 1971). It was interpreted as an igneous intrusion 2500-4000 meters below sea level that may outcrop on the south side of the ridge. Gough and Heirtzler (1969) believe that the magnetic data suggests large irregular strike-slip displacement parallel to the trench.

Seismic refraction studies (Ewing and others, 1960) indicate that the Cayman Ridge and Nicaraguan Plateau are composed of over 20 km of crustal material overlying mantle with anomalous seismic velocities. Significantly, the thinnest crust in the Caribbean (6 km) is beneath the floor of the Cayman Trench where it overlies mantle of normal seismic velocity (8.0-8.3 km/sec) (Fig. 13). Ewing and others (1960) concluded that the main crustal layer in this part of the Caribbean ranges from 5.8 to 7.2 km/sec with velocities increasing with depth. Above this layer is a region with great velocity variability which they speculated might be a sequence of differentially lithified sediments. However, the wide range of compressional wave velocities recorded denies a unique geophysical solution for the composition of the trench walls and floor.

The diversity of rock types recovered by dredging substantiates the variability in composition inferred from seismic studies. The geology of the Cayman Ridge, mid-Cayman spreading center (MCSC) and Nicaraguan Plateau have been determined utilizing previously published geophysical data, the depth and composition of dredged rocks, the geological sequence of these rocks, paleontologic and radiometric dates, stratigraphic evidence obtained from lithic

components within the sedimentary rocks, and data from oil company drilling.

Although interbedding, intrusion and local tectonism could complicate the geology, the lateral correlation of the dredged rocks is remarkable. The most striking fact revealed by petrographic and chemical analyses is that the rocks recovered from the walls of the trench (i.e., Cayman Ridge and Nicaraguan Plateau) represent a completely different petrographic province compared to those recovered from the trench floor. The walls are composed of plutonic, volcanic, sedimentary and carbonate rocks typically found in island arcs and continental margins such as the Greater Antilles and Central America. In contrast, the mid-Cayman spreading center is composed of mafic and ultramafic rocks identical to those described from the major ocean basins.

PETROGRAPHY AND STRATIGRAPHY

Locations, depths of recovery, the descriptions of the rocks dredged from the Cayman Trench are too lengthy to be published here but are available upon request from the G.S.A. depository or the authors. To facilitate discussion of the numerous rock types, the station locations were separated into four morphotectonic regions: Eastern Cayman Trench, Cayman Ridge, Nicaraguan Plateau and mid-Cayman spreading center. The rocks recovered were divided into eight major types in the schematic stratigraphic cross-sections in figures 4, 5 and 6. Each region is discussed separately and the petrographic descriptions that follow begin with rocks that are stratigraphically lowest or intruded into the section.

Eastern Cayman Trench

The rocks recovered within the easternmost section of the Cayman Trench immediately south of the Sierra Maestra (3400-6600m) are predominantly granodiorites, tonalites and basalts exhibiting various degrees of alteration and metamorphism (1,2,3,4).^{*} Limestone, large manganese nodules, thick manganese plates, and coral were sampled at shallower depths, on a mid-trench elevation, between the Sierra Maestra and Jamaica (5,6,7).

Fresh samples of granodiorite are medium grained, hypidomorphic-granular and composed of plagioclase, amphibole, orthoclase, and quartz with minor opaques. Chlorite, epidote and sericite are secondary alteration products. Many of the granodiorites and tonalites have been hydrothermally altered and some also show the effects of cataclasis. These sheared metaplutonics are almost entirely composed of chlorite and epidote with minor amounts of granular polycrystalline quartz, amphibole, opaques and relict plagioclase.

At two localities meta-igneous rocks were recovered. Some are metabasalts with sodium-enriched plagioclase and unalitized pyroxene phenocrysts set in a fine matrix of chlorite, epidote, sericite and opaques. Others are blastoporphyrific with relict plagioclase and pyroxene phenocrysts in a groundmass that is often plagioclase-rich with secondary chlorite and epidote aggregates. Embayed quartz phenocrysts (xenocrysts ?) also occur in these meta-volcanics. On a tectonic high within the trench (5), fine-grained chlorite schists outcrop and appear to

^{*}Numbers in parenthesis refer to dredge station numbers on figures 2,4,5 and 6 and in the unpublished appendix.

be the metamorphic equivalent of the granodiorites recovered to the north. Thick manganese plates, manganese encrusted limestones and corals were dredged from shallower portions of the same escarpment (6,7).

Cayman Ridge

West of Sierra Maestra, along the Cayman Ridge, rock types become increasingly diverse. However, major rock units and, in some cases individual types can be correlated all along the ridge. In particular, the limestones prove to be excellent time-stratigraphic units.

Metamorphics and plutonics with lesser amounts of volcanics, volcanics and shallow water Late Cretaceous and Late Paleocene shallow-water carbonates outcrop along the deepest parts (> 2500 m.) of the Cayman Ridge. Amphibolites, gneisses, and micaceous schists (18, 37, 40) were recovered with plutonic rocks along the western end of the ridge. Schistosity and compositional banding are common. A few gneisses (22, 40) have relict igneous textures and mineralogies that suggest they may have been granodiorites.

Although compositions range from gabbro (18) to adamellite (23, 37) the predominant rock type recovered was a medium to coarse grained hypautomorphic-granular granodiorite composed of zoned plagioclase, green and brown hornblende, potassium feldspar and quartz with minor biotite, epidote, clinozoisite, calcite, sericite and opaques (Fig. 7b). Sphene, apatite, monazite and zircon are common accessories and apatite may constitute up to 5 per cent in some of the more altered samples (39). Greenschist-grade metamorphism and cataclastic textures, similar to those described south of Sierra Maestra, occur frequently in the plutonic rocks.

At shallower depths (< 3000 m.), a great variety of interbedded volcanic, clastic and volcanoclastic rocks outcrop. Greenschists-facies metabasalts (17, 24, 42) and metavolcanics (9, 16, 23, 42) were commonly recovered with fresh volcanics but exhibit no preferred spatial relations along the ridge. Extrusives range in composition from basalt (17, 19, 29) to rhyolite (aplitic) (9) but the majority are andesites or dacites (15, 18, 20, 24, 25, 41, 42, 43). Phenocrysts of plagioclase, pyroxene and hornblende are often pseudomorphed during low-grade metamorphism (Fig. 7c). However, potassium feldspar and quartz phenocrysts, which are generally deeply embayed, tend to survive alteration (Fig. 7d). Quite a few samples are trachytic or subtrachytic (20, 23, 42) and one appears flow banded in hand specimen (42). Commonly, the metavolcanics are blastoporphyritic with the original mesostasis recrystallized to a fine felsic, chloritic or cryptocrystalline groundmass. Many of the volcanics are purple or reddish in color due to enrichment of oxidized mafic and opaque minerals. These are indicated by the letter "R" in figures 4, 5 and 6. At two sites (20, 23) igneous contacts with the surrounding units were recognized.

Pyroclastics (41, 42, 43) exhibit vitroclastic textures and many have undergone various degrees of alteration and devitrification (9, 15, 17, 22, 24, 41, 43). Folded lappili tuffs (15, 22) have been so altered that only sinuous flakey masses of chlorite and a few mineral grains remain in a clay matrix (Fig. 7a). Tuffs contain a large lithic component and some are intercalated with microfossil-bearing carbonates and clays (24).

The greatest variety of rock types recovered were sedimentary and apparently outcrop all along the Cayman Ridge. Volcanic breccia, conglomerate, arenite and argillite are ubiquitous and primarily composed of igneous fragments with subordinate amounts of mineral, clastic, metamorphic and biogenic clasts in clay matrices. Non-volcanic argillite, graywacke, arkose and conglomerate are also common.

Significantly, many of the clastic rocks have "red bed" equivalents which are delineated with an "R" in figures 4, 5 and 6. The distinction between pyroclastics, vitrophyric lavas and erosional volcanoclastics (epiclastics) becomes increasingly difficult ^{to make} as weathering and alteration become more intense. Therefore, where a distinction could not be made on petrographic criteria alone, the rock was simply called a volcanoclastic. (Fisher, 1961; Pittijohn and others, 1973).

The clasts that comprise the volcanoclastic and sedimentary rocks were probably derived from the older underlying volcanics and plutonics. Significantly, coarse volcanic breccias (15, 16, 23, 24, 25) and conglomerates (23, 24) contain fragments of rocks similar to those dredged at other sites and some that were not previously recovered. Thus, parts of the geologic history can be pieced together from clast investigations (c.f. lunar breccia studies).

Carbonaceous matter is a minor clastic component although calcite is often a cement. A few of the conglomerates and breccias (23, 24, 25) contain fragments of older sedimentary rocks and limestones (Eocene-Oligocene) and thus have been

placed higher in the stratigraphic columns. Although some local stratigraphic sequences can be recognized, an attempt to refine the stratigraphy within the volcanics and clastics on a regional scale is difficult.

Carbonates. The dredged limestones fall into three major groups according to depositional environments: 1) young deep-water open-ocean types, 2) shallow-water varieties, and 3) recent semiconsolidated carbonates associated with living organisms. Some are non-diagnostic of environment or were undateable. Late Cretaceous to Oligocene and some Miocene limestones (9, 17, 23, 33, 38, 26, 40, 41, 43, 42) are predominantly biomicrites showing partial dissolution and recrystallization of shallow water and meritic fossils. They contain small percentages of algae, bryozoa, echinoids, miliolids, lithic and mineral fragments and are characteristic of a shallow, carbonate bank or shelf environment.

Miocene, Pliocene and Pleistocene limestones (9, 15, 16, 20, 21, 22, 27, 30, 33, 41, 39, 33, 37, 42) are generally micritic, planktonic oozes that may show extensive test and matrix dissolution with subsequent sparry recrystallization. There are traces of larger shell, lithic and mineral fragments. A few samples show the effects of bioturbation and redeposition of older microfossils. Curiously, many of the limestones from the western end of the ridge (37, 38, 42, 43) have been phosphatized, silicified and manganese encrusted. These limestones were recovered with silicified and phosphatized carbonate breccias that appeared to be a crust unconformably underlying the limestone. The Miocene limestones are from either deep, open-ocean, or shallow-water

environments and in some cases appear to be transitional (neritic) between the two (21). One sample (23) contains a mixture of Eocene-Miocene shallow-water and open-sea pelagic forams.

Pleistocene to Recent carbonates are either pelagic oozes (16, 15, 20, 21, 22, 26, 27, 30, 32, 34, 43) or reefy limestones with abundant shallow-water biologic material such as coquina, sponges, coral, algal balls, sea biscuits, echinoids, and mollusk shells (10, 11, 12, 13, 14). Deep water corals and sponges were recovered from sites 10, 16, 35, 36.

In general, shallow-water carbonates were recovered above 1000 meters from active reef-producing banks such as Misteriosa and Rosario. Below that level, pelagic oozes commonly associated with open-ocean environments, were prevalent.

Nicaraguan Plateau

Considering the distances involved and randomness of sampling inherent in dredging, the rocks recovered from the north side of the Nicaraguan Plateau are remarkably similar to those from the Cayman Ridge. Schistose metamorphics and plutonic rocks are noticeably absent from the stratigraphic section (Fig. 5) or possibly were not sampled. However, abundant breccias, wackes and arenites (53, 54, 55, 56, 57) contain much detrital material indicative of granitic and metamorphic sources. Most of the metamorphics are low-grade greenschists equivalent to sediments (55) and volcanics (48, 50) recovered at nearby localities or within the same dredge haul. Shearing and cataclasis is evident even among non-metamorphosed rocks. A quartzite, composed of fragmental, recrystallized quartz in a polycrystalline quartz groundmass with

minor opaque bands was recovered at site 56. Carbonates, which are generally fossiliferous micritic limestones, exhibit various degrees of recrystallization (48, 59, 61, 60, 62).

The most abundant sedimentary rock types sampled along the Nicaraguan Plateau are arenites (including calcarenites) and graywackes which are interbedded with lesser amounts of argillite and carbonates. Graywackes grade into microbreccias (53, 54, 55) and conglomerates (44, 55). As on the Cayman Ridge, oxidation of abundant ^{iron} ~~iron~~ oxides and red-brown clay impart a reddish color to some of the breccias and wackes. Clastic carbonates and sedimentary rocks with carbonate cement were more frequently recovered here than from the Cayman Ridge. Tuffs and tuffaceous clastic rocks (47, 50, 55, 59, 60, 63) are also more common, whereas, extrusive volcanics are less abundant. A limestone sequence, similar to that of the Cayman Ridge, comprises the upper units of the Plateau, but fewer datable samples were recovered here. Possible Late Cretaceous, Eocene and Oligocene shallow-water carbonates were recovered below 3,000 m with the breccias, wackes and arenites. Late Oligocene to Recent pelagic deep-water limestones are interbedded with minor clastics and apparently outcrop at shallower levels along the south wall of the trench. A number of Early-to Mid-Miocene and Neogene calcarenites were recovered with these open-ocean limestones.

Redbeds and simiconsolidated, friable arenites, which are often well sorted, graded and bedded, outcrop nearest to western Jamaica (44, 45, 46). To the west (47, 48, 49, 50, 55, 56), low-grade metamorphism, folding and cataclasis becomes apparent.

Volcanics and metavolcanics (48, 49, 50) primarily outcrop around 80°58'W, but are common constituents in the clastic rocks.

Well-bedded sedimentary rocks that appear to be turbidites (54, 55) predominate further west. Granite and metamorphic components are markedly increased in these units.

Biogenic and clastic carbonates with tuffs outcrop east of Swan Island (59, 60, 61, 62). Just west (63) of the island, where the slope drops off rapidly, a haul of turbidite-like rocks (similar to 54, 55) with Oligocene microfossils was recovered.

Carbonates. Abundant clastic carbonates, including calcilutite (48, 59), calcarenite (60, 47, 57, 61, 62, 59), and calcareous conglomerate (57) are interbedded with and in some cases may underlie the non-calcareous clastics. Interbedding of calcarenite and calcilutite on a small scale is evident in hand specimens from sites 48 and 59. These clastic carbonates are well sorted and may contain minor amounts of plagioclase, quartz, epidote, chlorite, glass shards and opaques. Some have bands of marly or ferruginous oxidized material and a few have small lenses filled with quartz or euhedral sulphides.

The oldest carbonate recovered is possibly Late Cretaceous but recrystallization has partially obscured the microfossils. A calcareous conglomerate, also recovered from below 3,000 m (57), contains fragments of limestone, calcarenite, sparry calcite with minor fossils, quartz, orthoclase and plagioclase. It has been dated as Oligocene, while a fossiliferous graywacke at the same locality yielded Eocene shallow-water fossils. Late Oligocene bioclastic limestones containing microfossils characteristic of

deep open-water environments were dredged from below 2500 m at sites 52, 53, and 60. A turbidite-like assemblage of clastic rocks west of Swan Islands also contained Oligocene microfossils. Early-to Middle-Miocene and Neogene fine-grained, laminated limestones and calcarenites recovered at sites 59, 60, 61 and 62 are characteristic of deep-open sea environments. The remaining limestones are foraminiferal oozes (45, 46, 58, 61, 62), some of which are semiconsolidated, and micrites (60, 62), which are often recrystallized, that generally outcrop above 3,000 meters. They range in age from Early Miocene to Recent. A number of other oozes (48, 50, 52, 59, 56) recovered did not contain diagnostic fossils. Limestones at sites 59, 60 and 63 were recovered with abundant tuffs and often contained glass shards. One fossiliferous tuff (60) contains sparse Early-to Mid-Miocene coccoliths.

Mid-Cayman Spreading Center

While the similarity of lithologies between the Cayman Ridge and Nicaraguan Plateau and the diversity of rock types are surprising, the unvarying nature of the rocks outcropping on the steep, sediment-free walls of the mid-Cayman spreading center is astonishing and of more than local interest. Successful recovery at sixteen localities in the center and along the north and south edges of the trench suggests a crustal sequence identical to that reported for the mid-oceanic ridge (Perfit and others, 1974). The petrography, major element variations and trace element abundances further substantiate their abyssal tholeiitic nature and suggest that they were derived as primary melts in the upper mantle (Perfit, 1977).

Primarily serpentinite and serpentinitized peridotites (65, 66, 67, 68) were recovered with minor quantities of graywacke and basalt from the Oriente fracture zone. Fragments of similar ultramafics have previously been recovered by Eggler and others (1973). Deep along the walls of the mid-Cayman spreading center, serpentinitized peridotite (72, 74) and coarse gabbro (71, 72, 75) (Fig. 7f) were dredged. Dolerite (71, 72, 73, 74, 76) and basalt (71, 72, 73, 75, 78, 79) (Fig. 7e) outcrop somewhat higher along the steep escarpments. Samples recovered from sites 75 through 80 were dredged from the proposed axial rift valley. Lesser amounts of metavolcanic, metasediment, marble and limestone were sampled on the tops of the ridges.

Carbonates. The amount of carbonate dredged from the mid-Cayman spreading center was slight and difficult to identify as in situ. Most are micritic limestones with pelagic forams and minor angular fragments of plagioclase, clinopyroxene, chlorite, iddingsite, amphibole and epidote. A lack of shallow-water fossils and granitic detritus suggests that these limestones formed within the trench. A calcareous breccia containing basalt fragments was recovered at site 78. A few of the limestones contained datable pelagic forams: a Miocene-Pliocene marly limestone (75), a possible Miocene micritic limestone (73) and a Pliocene micritic limestone (72).

RADIOMETRIC AGES

Whole rock and mineral potassium-argon ages of a tonalite, four granodiorites and a schistose amphibolite were determined to date tectonism and plutonism in the Cayman Trench and to relate

the ages to those dates obtained from surrounding regions. The radiometric results are presented in table 1 and the ages are plotted in figures 4, 5, and 6. The tonalite (E438-1), from the floor of the trench south of Sierra Maestra, is the oldest at 83 ± 2 million years. It correlates well with absolute ages of metamorphics and plutonics from the Greater Antilles which have been related to the onset of the Late Cretaceous Laramide Orogeny (Lewis and others, 1973; Kudholey and Meyerhoff, 1971). Granodiorites from four localities on the western Cayman Ridge (sites 32, 37, 39, 40) gave ages around Early Paleocene which compare favorably with similar rocks from the well-documented Laramide event in Central America (Harland and others, 1964; Dengo and Bohnenberger, 1969). Potassium-argon dates on separate mineral phases substantiate the whole rock dates and indicate that the latter are crystallization ages.

A biotite-bearing amphibolite recovered with granodiorite at site 40 was determined to be 69 ± 9 million years old, which is similar to ages published for the Westphalia schist in Jamaica (Lewis and other, 1973). The error involved in dating does not allow us to separate metamorphic and plutonic events, more likely, the Laramide Orogeny caused widespread concurrent plutonism and metamorphism over an extended period of time.

SEISMIC CORRELATION

The generalized stratigraphy proposed here compares favorably with previously determined seismic sections of the trench (Fig. 8). It is also now possible to correlate specific seismic velocity (V_p) layers with actual rock types recovered from the trench floor and walls (Fig. 9).

The Nicaraguan Plateau is divided into a thin (≤ 1 km) low velocity layer (3.9-4.8 km/sec) overlying a 1-2 km thick 5.1-5.4 km/sec layer which in turn overlies 6.2-6.7 km/sec crust estimated to be 10-15 kilometers thick (Fig. 8). There is evidence that this thick layer is arched or folded into two ridges beneath the Nicaraguan Plateau (Arden, 1969). The northern ridge forms part of the south wall of the Cayman Trench and is separated from the southern ridge by a great deal of 4-5 km/sec material (Ewing and others, 1960). Although the velocities of the deepest layers are comparable to oceanic crustal velocities, the thickness of the Plateau is three times greater than that recorded in the ocean basins. At deeper levels, velocities from 7.2 to 7.6 km/sec were recorded.

Seismic velocities and layer thicknesses measured on the Cayman Ridge differ slightly from those of the Nicaraguan Plateau (Fig. 8.). An upper 1-2 km thick 4.6-5.5 km/sec velocity layer overlies a 6.2-6.5 km/sec crustal layer; velocities then increase to 7.2 km/sec at a depth of 17 km. In some places an uppermost seismic layer of 3.5-3.8 km/sec recorded.

It is evident that the geology of the Cayman Ridge and Nicaraguan Plateau is much more complicated than the seismic studies indicate. At low confining pressures (.5-2.0 Kb), laboratory compressional wave velocities of granodiorite, similar to those recovered, range from 6.0-6.4 km/sec and low grade schists may range from 5.3 to 7.3 km/sec. Amphibolites at 1 to 2 Kb have slightly higher velocities from 6.2-7.5 km/sec (Anderson and Lieberman, 1968; Birch, 1961). Because of their occurrence in

outcrops, all of the above rock types appear to be good candidates for the unexposed lower crustal layers of the Nicaraguan Plateau and Cayman Ridge (Fig. 9). Increased pressure and metamorphic grade can account for the high velocities (7.2-7.6 km) recorded at depths greater than 15 km. The 1-2 km thick overlying unit could be composed of the interbedded volcanics, volcanoclastics and sediments that were recovered, many of which show slight degrees of metamorphism. These rocks could have velocities from 3.7 to 6.0 km/sec and a great many in the 4.5-5.7 km/sec range, although one might expect somewhat lower velocities for the sedimentary rocks. Indurated limestone could also fit into this seismic layer. The measured seismic velocities for this layer (5.1-5.4 and 4.6-5.5 km/sec) probably represent the average velocity for a layer with complex lithologic relations that cannot be resolved by conventional seismic refraction techniques.

The discontinuous, thin upper layer is likely to be less consolidated sediments and carbonates with minor volcanics. Such a unit could have a highly variable velocity structure from about 1.6 km/sec for unconsolidated sediments to 6.0 km/sec for indurated limestone. The measured velocities of 3.9-4.8 km/sec (N.P.) and 3.5-3.8 km/sec (C.R.) represent average velocities for the limestones recovered on the upper slopes of the plateau and ridge.

The thin, uppermost 2.0 km/sec layer includes ooze and marl, but sampling indicates that indurated and phosphatized limestones also outcrop in the uppermost layer which should produce higher velocities than those recorded.

The velocity structure of the Cayman Trench floor is characterized by a thin (~ 2 km) 4.4-5.5 km/sec layer underlain by a 4-6 kilometer thick 6.2-6.8 km/sec layer which overlies a layer with normal mantle velocities (8.0-8.3 km/sec) (Fig. 8). Often, a thin (~ 1 km) uppermost layer with velocities from 3.0 to 3.3 km/sec was recorded but did not appear to be continuous along the trench (Ewing and others, 1960). This velocity structure is very similar to that recorded in the crust of major ocean basins (Ewing and Ewing, 1959; Raitt, 1963; Hill, 1957).

Pelagic limestone (2.8-5.6 km/sec) and variously consolidated or metamorphosed sediments and volcanoclastics (1.6-4.0) comprise the thin uppermost non-continuous 3.0 to 3.3 km/sec layer. At calculated in situ confining pressures of .25-1 Kb, the compressional wave velocities of weathered and metamorphosed basalt and dolerite ranges from 4.3 to 6.2 km/sec and 4.7 to 5.8 km/sec for fresh basalt (Fox and others, 1973), and consequently they are likely to comprise the 4.4-5.5 km/sec layer (Fig. 8). At 1-2 Kb, gabbros with velocities from 6.7-7.03 km/sec and metagabbros from 5.87-6.6 km/sec are likely to represent the 6.2-6.8 km/sec basement layer. Amphibolites (6.2-7.5 km/sec) are also a candidate for this layer, although only partially amphibolitized gabbros were recovered.

Cataclastic metagabbro (5.4 km/sec at 1-2 Kb), serpentinites and serpentinitized peridotites (3.55-4.76 km/sec at .5-7 Kb) have velocities which are too low to be a significant component of the 6.2-6.8 km/sec layer (Fox and others, 1973) but anorthositic rocks with velocities of 6.62-6.81 km/sec are compatible with the published crustal velocities. Although un-serpentinitized peridotite

was not dredged, it has velocities of 8.0-8.3 km/sec and may comprise the upper mantle beneath the trench.

PRE-TERTIARY GEOLOGY OF THE NORTHERN CARIBBEAN MARGIN

The oldest datable rocks dredged were Late Cretaceous and Paleocene shallow water limestones, recovered from deep along the western Cayman Ridge, and a possible Late Cretaceous pelagic limestone from the Nicaraguan Plateau. On the Cayman Ridge the limestones are associated with volcanics, some of which are extremely oxidized, and clastics, often red, with predominantly volcanic detritus. Just to the east, along the Ridge, Late Cretaceous to Paleocene metamorphics and granodiorites were dredged with younger limestones and relatively fewer volcanics. Identical granodiorites of Late Cretaceous age dredged within the eastern section of the trench and abundant immature granitic clasts and detritus in the sedimentary rock along the Cayman Ridge and Nicaraguan Plateau suggest great lateral extent of these intrusives. Previously, the existence of crystalline basement beneath the Cayman Ridge had only been inferred from magnetic and seismic data by Falquist and Davis, (1971).

Amphibolite-grade metamorphic rocks that were recovered with the granitic plutonic rocks may represent pre-Late Cretaceous lavas and sediments that were metamorphized and uplifted during the Laramide Orogeny. We feel that it is reasonable to assume that at least part of the 15 kilometers of buried crust beneath the Cayman Ridge and Nicaraguan Plateau is older than Late Cretaceous.

Arden (1969, 1975) and recent drill data (unpublished) show that a sequence of volcanics and clastics interbedded with early Cretaceous pelagics comprise the oldest section sampled on the Nicaraguan Plateau. This sequence is overlain by discontinuous lenses of volcanics and erosional clastics, including red beds of Mid-to Late Cretaceous Age. This correlates well with the red volcanics and clastics recovered with Late Cretaceous limestone on the west end of the Cayman Ridge. A Late Cretaceous volcanic center in the Pedro Bank area proposed by Arden (1969) also correlates with our recovery of abundant volcanics around $80^{\circ}58'W$ and $17^{\circ}48'N$ on the north flank of the Nicaraguan Plateau. To the southeast, granodiorite has been drilled at 1973 meters in Pedro Banks -1 well ($78^{\circ}48'W$, $16^{\circ}56.2'N$), and is overlain by a 53 meters of conglomerate and 1920 meters of Tertiary limestone. Altered porphyritic granodiorite has also been recovered at 2021 meters under a middle Eocene sequence of shale and limestone beneath the western Nicaraguan Plateau, ($81^{\circ}41.2'W$, $14^{\circ}52.4'N$) (Arden, 1975).

Although many of the igneous and metamorphic clasts observed in the sedimentary rocks may actually be from terrains much older than Cretaceous, only the post-Jurassic history of the trench can be readily deciphered. The Cretaceous-Paleocene plutonics, metamorphics and volcanics were formed during the Laramide orogenic event that is well documented in Central America and the Greater Antilles. Greenschist-facies metamorphism and cataclasis of some plutonics and many of the surrounding volcanics and clastics indicates that local tectonism continued at least into the early Tertiary.

Central America

In Central America, the oldest rocks exposed are metamorphosed Lower Paleozoic sedimentary rocks and granitic intrusives, unconformably overlain by Late Paleozoic sedimentary rocks (Dengo and Bohnenber, 1969; Mills and others, 1967; McBirney and Bass, 1969; Wilson, 1974). These comprise the so called "Nuclear Central American foreland" (Schuchert, 1935) which presently outcrops in primarily east-west trending mountain ranges that include the Sierra Madre del Sur in Mexico, Sierra Chuacus and Sierra las Minas in Guatemala, and the Sierra Merenden and Sierra Omoa in Honduras. This belt of mountains forms a structural arc which is concave to the south (Kesler, 1971). They strike eastward offshore where they seemingly continue along the Nicaraguan Plateau and are bounded on the North by the Polochic and Motagua fault zones which appear to be contiguous with the Cayman Trench (Mills and others, 1967; Donnelly and others, 1968; Muehlberger and Ritche, 1975; Schwartz and Newcomb, 1973; Dengo and Bohnenberger, 1969). The Northern Sierras in Guatemala and the Maya Mountains in British Honduras appear to extend seaward and continue as the Cayman Ridge.

The strike, relative relief and structural trends of the Sierras of Northern Central America led Meyerhoff (1966), Mills (1967), Dengo and Bohnenberger (1969) and Kudholey and Meyerhoff (1971) to postulate that the Cayman Ridge and Nicaraguan Plateau are remnants of the Paleozoic Nuclear foreland which remained as positive features throughout the Mesozoic and Early Cenozoic.

The Mesozoic sedimentary record in Central America is poorly known and few reliable paleontological dates exist. The early

Mesozoic, in Central America, is generally considered a time of emergence associated with deposition of shallow marine and flood plain shales and sandstones (Mills, 1967; Wilson, 1974).

Wilson (1974) suggests that Lower Cretaceous sedimentation in Central America is characterized by deposition of shallow water carbonates and evaporites on a broad tranquil shelf with localized regions of deep water pelagic sedimentation to the South and East in Middle to Late Albian. Coarse clastics and volcanics unconformably overlying the carbonates indicate a period of tectonic disturbance and volcanism in the Early to Middle Cenomanian which separates Lower from Upper Cretaceous carbonate platform sedimentation. This stratigraphic sequence is remarkably similar to that determined for the oldest part of the Nicaraguan Plateau-Cayman Ridge. Furthermore, the effects of a Mid to Late Cretaceous orogenic event seen in the geology of Central America and the Greater Antilles have been recognized in the Cayman Trench sequence.

Early in the Late Cretaceous (Turonian-Santonian) a deep, fault-controlled trough existed along the present Polochic-Motagua fault zone that trends northeast across Guatemala and Honduras toward the Cayman Trench. It was the locus for submarine volcanism and eugeosynclinal sedimentation which included carbonate turbidites from the north and exotic igneous blocks and turbidites from the steeper southern side of the trough (Dengo and Bohnenberger, 1969; Wilson, 1974).

The Polochic and Motagua fault zones have been postulated to be regions of crustal weakness, associated with possible trans-current, normal and/or reverse faulting, that are at least Paleozoic in age. A large degree of left-lateral megashear has

been proposed in the Late Paleozoic-Early Mesozoic (Walper and Rowett, 1972; Kesler, 1971) and others suggested major displacement of Paleozoic basement and Pre-Cretaceous units since the Cretaceous (Malfait and Dinkleman, 1972; Pinet, 1972; Holcombe and others, 1973; Silver, 1974).

Recent detailed field studies (Schwartz and Newcomb, 1972; Lawrence, 1975; Newcomb, 1975; Schwarz, 1976) suggest that the Motagua fault zone represents a Late Cretaceous suture between two lithospheric plates that was associated with extensive southward thrust faulting and relatively little strike-slip movement. Newcomb (1975) shows that, north of the fault zone, the Chuacus group probably of Paleozoic age, underwent at least two periods of deformation, the second of which occurred in the Late Mesozoic and was associated with widespread cataclasis and retrograde metamorphism. Furthermore, this group is not lithologically or metamorphically correlative with the Paleozoic Las Ovejas complex south of the fault zone.

Schwartz and Newcomb (1973) Lawrence (1975) suggest that siliceous shale, chert, basaltic tuff (?), basic schist, amphibolite, serpentinites and blueschist to eclogite facies basalts of the El Tambor Formation, are fragments of oceanic crust that were metamorphosed in a Mesozoic subduction zone (marked by the present Motagua Fault zone) and thrust southward over the Las Ovejas complex as two continental plates collided in the Late Cretaceous. This convergent zone is associated with numerous Mid-Cretaceous to Tertiary "granitic" plutons south of the fault zone that swing across central and southern Guatemala into northern Honduras, and east toward the Cayman

Trench (Williams and McBirney, 1969; Dengo and Bohnenberger, 1969). Intrusion accompanied and aided large scale uplift which resulted in rapid erosion and restricted carbonate bank formation.

Few Campanian-Maestrichtian marine deposits are known in southern Guatemala and Honduras, attesting to the emergent nature of Central America at that time. Continued uplift, thrusting and intrusion caused a shift of the depositional trough to the north at the close of the Cretaceous, where thick flysch sequences of conglomerate, sandstone, shale and calcarenite were deposited in shallow elongate marine basins (Dengo and Bohnenberger, 1969; Wilson, 1974). An analogous event was apparently occurring at the same time to the east along the Nicaraguan Plateau-Cayman Ridge.

Bay Islands, Western Nicaraguan Plateau

The Bay Islands, that sit on the Bonacca Ridge, have Cretaceous lithologies that are analogous to those of the Motagua Valley and the Cayman Ridge. The islands of Roatan and Guanaja are composed of variously metamorphosed sediments, carbonates and igneous rocks intruded by granitic dikes, metagabbro and serpentinite which in turn are overlain by Pre-Tertiary and Tertiary limestone and conglomerate (McBirney and Bass, 1969). The overlying Pre-Tertiary conglomerates primarily contain clasts of schist, quartz and other metamorphics, and they are often interbedded with mudstone and shale, similar to the rocks dredged to the east near Swan Island.

The more intensely metamorphosed rocks and serpentinites are often oriented parallel to thrust faults which are aligned with the trench axis. On Roatan, amphibolites with mafic and

ultramafic affinities are locally intruded by pegmatitic and aplitic dikes, and on Guanaja a hornblende gabbro and associated dikes cut the metasediments. Although the ages of intrusion and metamorphism are not certain here, the lithology and structural relations are nearly identical to those of the western Cayman Ridge (McBirney, personal communication). Horne and others (1974) indicate that a discontinuous east-northeast trending chain of Late Cretaceous to Early Tertiary (36-93 m.y.) undeformed plutons intrude Paleozoic metamorphics in the postulated landward extension of the Bonocca Ridge in northern Honduras.

Jamaica, eastern Nicaraguan Plateau

The oldest exposed rocks in Jamaica are Early Cretaceous shallow marine limestones and Cretaceous clastics and volcanics that appear as inliers in the overlying Tertiary limestones. Volcanic rocks include water-laid tuffs, ash-flow tuffs, fewer dacites and andesites, and rare basalts. Some of these are flows, such as in the Early Cretaceous Devils Race Course formation. Rudist limestone, volcanic conglomerate and breccia, and lesser amounts of sandstone and shale are commonly interbedded with the volcanics. This succession is intruded by predominantly granodiorite plutons of Late Cretaceous to Paleocene age. The Blue Mountain Inlier in eastern Jamaica contains altered and sheared Cretaceous volcanics, serpentinites and basic greenschists in the north and higher grade metamorphics and associated nearby intrusive rocks in the south (Zans and others, 1962; Roobol, 1972). These later metamorphics, known as the Westphalia Schists, are amphibolite-grade quartzo-feldspathic and basic rocks.

Potassium-argon dating done by Lewis and others (1973) suggests a minimum age of 76.5 m.y. for these schists with subsequent resetting of biotites during local tectonic events in the Eocene about 50 m.y. ago. Absolute age dates from the Ginger Ridge granodiorite and surrounding hornfels in the Central Inlier reveal a similar situation with presumably reset hornblende yielding a potassium-argon date of 47 m.y. and granodiorite whole rock and biotite hornfels ages around 85 m.y. Chubb and Burke (1963) published an age of 65 ± 5 m.y. for the Above Rocks granodiorite and 75 ± 5 m.y. for the Flint River granodiorite.

Not only are these ages close to those determined for the granodiorites and schists from the Cayman Trench (table 1), but they are all petrographically similar. Furthermore, the abundant conglomerates, which contain primarily volcanic clasts, interbedded with tuffs, shallow-water limestone and minor lavas in Jamaica are essentially the same assemblage of pre-Tertiary(?) rocks dredged in the Trench.

Southern Cuba, Northeast Wall of the Cayman Trench

Ages of the oldest rocks in Cuba have been widely disputed and estimates range from Paleozoic to Jurassic (Skvor, 1969; Hatten and Meyerhoff, 1970; Skvor, 1970; Khudoley and Meyerhoff, 1971; Iturralde-Vincent, 1975). Regional attempts at correlating these rocks with those of Central America have been equally tenuous. It is fairly certain that at least western Cuba had an older and much more complex history than the rest of the Greater Antilles. However, the Oriente Province in southeastern Cuba has had an active geologic history similar to Jamaica and Hispaniola

since the Cretaceous. In the Early Cretaceous the southern margin of Oriente and eastern Jamaica were sites of eugeosynclinal sedimentation and eruption separated from shallow platform environments, to the north and west respectively, by emergent volcanic arcs (Zans and others, 1962; Kudholey and Meyerhoff, 1971; Mattson, 1973; Pardo, 1975). Mid-to Late Cretaceous orogenesis caused contemporaneous granitic intrusion, increased volcanism, metamorphism, folding and serpentinite emplacement related to northward thrust faulting. The association of basic schists, and lavas, amphibolites and serpentinites intruded by granitic plutonic rocks in a severely tectonized region is strikingly similar to the situation described along the Motagua-Polochic fault zone, on the Bay Islands and in the Blue Mountains of Jamaica. An ultrabasic complex overlain by pillow basalt and associated with mobilized serpentinites appears to have been oceanic crust that was thrust upward during Late Cretaceous to Middle Eocene (Pardo, 1975).

CENOZOIC HISTORY OF THE CAYMAN TRENCH AREA

In Central America and the Greater Antilles, volcanism, emergence and local deformation sporadically continued until the Late Eocene-Oligocene when most volcanism stopped and the sea floor began to subside. Rapid deposition occurred in fault controlled basins and volcanism apparently was associated with local vertical tectonics (Mills and others, 1967; Dengo, 1969; Dengo and Bohnenberger, 1969). Extensive block faulting and "andesitic" volcanism occurred in a broad southwest to northeast arc in Guatemala, Honduras and Nicaragua (McBirney and Williams, 1965; Mills and others, 1967; Williams and McBirney, 1969).

Pinet (1975) suggests that basement and pre-orogenic rocks on the continental margin of Honduras that were deformed in the Lower Cretaceous to Early Eocene convergent event, began to subside in the Mid-Tertiary and were block faulted in the Pliocene.

A thick Early Tertiary clastic wedge implies a continuation of the sedimentary regime that began in the Late Cretaceous. Eocene conglomerates, sandstone, shale and clastic carbonates were deposited in deep grabens and basins following the trend of the Motagua Fault Zone, while to the north in British Honduras, northern Guatemala and southern Mexico shallow-water carbonate and evaporite sedimentation continued (Wilson, 1974). Significantly, the clastic rocks are often red beds and contain considerable volcanic detritus from the subaerial erosion of Upper Cretaceous-Early Tertiary volcanoes in Guatemala, Honduras and Nicaragua (Mills and others, 1976; Dengo and Bohnenberger, 1969).

Late Tertiary sedimentation was characterized by terrigenous, deltaic and local reefal or lagoonal environments of deposition. Interbedding of conglomeratic red beds, with red and brown arkose, sandstone, siltstone and shale was common (Vinson, 1962). Block faulting and volcanism continued throughout Honduras through most of the Miocene (Mills, 1967). By Pliocene, the seas had withdrawn and sedimentation decreased in eastern Central America. However, the development of numerous volcanoes along the west coast of Central America (due to subduction along the newly formed or reoriented Middle Americas Trench in the Mid Tertiary) obscures much of the geology in Central America that can be related to the Cayman Trench.

The assemblage of Early Tertiary rocks recovered from the Cayman Ridge and Nicaraguan Plateau is primarily composed of coarse to medium grained sedimentary rocks with lesser amounts of volcanics and Eocene to Oligocene shallow-water limestones. However, a few Late Oligocene limestones recovered with clastics from the Nicaraguan Plateau were indicative of a deep-water pelagic depositional environment.

Each clastic rock type appears to have a red bed equivalent suggestive of subaerial and/or deltaic depositional environments. The major components in these rocks are lithic and crystal fragments probably derived from a wide variety of older volcanics and underlying plutonics. Fewer clasts of tuffs, metamorphics and carbonates were observed. The coarseness, angularity and freshness of many of the clasts is indicative of rapid erosion and deposition probably from a nearby emergent Cretaceous volcanic center. The presence of plutonic clasts suggests a great deal of erosion and uplift in order to expose the intrusives by the Eocene. Angular shallow-water limestone fragments in a few breccias and conglomerates support the idea of continued uplift, erosion and rapid deposition into the Early Tertiary. Contemporaneous volcanism and sedimentation are indicated by interbedded lavas and clastics, chilled margins in contact with thermally metamorphosed sediments and tuffaceous carbonates and shales.

Paleocene red beds and calcareous shales have been drilled beneath the Nicaraguan Plateau (Arden, 1969, unpublished drill data). Andesite overlain by probable middle Eocene brown-red

sandstone and dark claystone were drilled at about 2000 m in Berta-1 well (82°04'W, 16°13'N) beneath the western Nicaraguan Plateau (Arden, 1975). The oldest Tertiary rocks in Jamaica are Lower Eocene, possibly Paleocene sandstones, breccias and conglomerates of the Wagwater formation, found in a deep (> 6500 m) fault-bounded trough traversing the eastern end of the island. These rocks are typically coarse volcanic red beds that grade upward into shales, volcanic sandstones and limestones of the Richmond Formation (Zans, and others, 1962; Green, 1972; Wright and Dickinson, 1972). Formation of this trough was accompanied by extrusion of lavas of predominantly andesitic composition and deposition of tuffs into the geosynclinal pile. Folding, thrust faulting and dynamic metamorphism locally affected these rocks as the Laramide orogeny climaxed in the Mid-Eocene. Petrographic comparison of Wagwater clastics and volcanics with the Paleogene clastics from the Cayman Ridge-Nicaraguan Plateau reveals their equivalence.

In Cuba, similar thick units of andesitic volcanics and volcanic rich clastics were deposited in a deep trough along the Cauto fault-basin, north of the Sierra Maestra, during the Late Cretaceous-Early Tertiary. To the north, shallow-water sedimentation and the growth of carbonate banks predominated. A volcanic arc, existed south of the Cauto Basin toward Jamaica and was associated with granodiorite and diorite plutonism (Bowin, 1968; Pardo, 1975). Volcanism stopped and southeast Cuba was uplifted by the close of the Eocene to form the present platform and Sierra Maestra (Kudholey and Meyerhoff, 1971; Mattson, 1973; Iturralde-Vincent, 1975; Pardo, 1975).

Although significant amounts of volcanics and clastics are absent in the upper Post-Oligocene section, a number of Early to Mid-Miocene fossiliferous tuffs recovered from both sides of the trench indicate that some volcanism continued into the relatively quiet Late Tertiary. Elsewhere, only Late Cenozoic alkaline extrusives associated with grabens in central Hispaniola have been reported (MacDonald and Melson, 1969).

Geologic histories of the Cayman Ridge and Nicaraguan Plateau differ slightly after the Eocene. On the Cayman Ridge, Eocene through Oligocene carbonates are indicative of a shallow-water environment while Pliocene through Pleistocene limestones were formed in a deep-water, open-sea environment. Miocene shallow-water, neritic and deep-water limestones mark a period of submergence. Consistent recovery of only shallow-water and reefal limestone from beneath the presently shallow reefs around Misteriosa and Rosario Banks suggest that reef building kept up with regional submergence in a few areas through the Tertiary. Abundant rounded pebbles and cobbles recovered along walls of the Cayman Ridge (sites 15, 16, 23, 24) were likely to have formed in the fluvial or active shallow marine environment. An Eocene-Miocene limestone recovered with them lends support to the existence of local shallow areas in the Miocene.

Eocene carbonates from the Nicaraguan Plateau were also formed in shallow-water environments but most Oligocene to Miocene carbonates had deep-water open-sea origins.

Possible turbidites, recovered west of the Swan Islands (63) which contain abundant Oligocene microfossils, support the

existence of a deep basin in the Oligocene. A number of Neogene and Miocene calcarenites may indicate local areas of emergence after the Oligocene; however, only Pliocene to recent open-sea pelagic limestones were dredged from the upper escarpments of the plateau.

Oligocene and Miocene shallow-water limestones outcrop on the Cayman Islands and deep-water Oligocene or Early Miocene calcareous mudstone overlying reef limestone comprises the bulk of the Swan Islands. Uplift of the Swan Islands during the Oligocene can also account for the turbidites found at the base of the islands. Both regions further attest to the existence of local vertical tectonics on the walls of the Cayman Trench since the Miocene.

Arden (1969, 1975) suggests that the Middle Eocene to Middle Miocene was primarily a period of carbonate sedimentation due to general submergence of the eastern Nicaraguan Plateau and Jamaica. Local short periods of uplift occurred in the Late Eocene and Late Oligocene forming basal carbonate conglomerates possibly similar to a Late Oligocene limestone recovered from site 52. These short tectonic events and intervening periods of carbonate sedimentation have also been recognized in southeast Cuba (Mattson, 1973; Kartashov and Mayo, 1972).

Uplift of the Nicaraguan Plateau initiated in the Middle Miocene caused renewed faulting, minor volcanism and deposition of shallow-water carbonate clastics until the latest Miocene (Zans and others, 1962; Arden, 1969). Miocene and Neogene calcarenites recovered from the Nicaraguan Plateau may be evidence for the

occurrence of this event. Jamaica, Hispaniola and Cuba have undergone local readjustments but generally have remained emergent since the Miocene whereas the Nicaraguan Plateau and Cayman Ridge have subsided and collected deep-water limestones.

Mid-Cayman Spreading Center

Petrologic, geochemical and geophysical evidence confirm the existence of an active east-west spreading center within the Cayman Trench rather than diapiric or tectonic intrusion of ultramafic mantle material (Bowin, 1968; Ericson and others, 1972; Eggler and others, 1973). Although the time of initiation of spreading is difficult to discern, a number of facts leads us to believe that the initiation of the trough that now forms the Cayman Trench began in the Eocene and the present configuration is post Eocene.

1. Abundant coarse Eocene clastics now found perched on steep escarpments along the walls of the Cayman Trench would have been deposited on the trench floor had it existed. It is more likely these sediments, which include red beds, are analogous to those deposited in Eocene grabens in Central America and the Greater Antilles.

2. Oligocene turbidites recovered west of the Swan Islands indicate that either a deep trough existed in the Oligocene or that there has been subsidence and faulting since the Oligocene.

3. Differences in the post-Eocene stratigraphy of the Nicaraguan Plateau and Cayman Ridge suggest that they could have been a single island arc that was split in the Eocene. Cuba and Hispaniola show a similar separation and lateral displacement since the Eocene (Malfait and Dinkleman, 1972).

4. Sediment cover on the trench floor is generally less than 200 meters thick.

5. The oldest limestone recovered from the floor of the trench is Miocene.

The Miocene-Pliocene limestone (75) recovered near the axial valley of the mid-Cayman spreading center implies an average east-west full spreading rate of .4 cm/yr for the last five million years. Assuming this average rate prevailed from Eocene (~50 m.y.b.p.) to the present, then the total eastward displacement of the Cayman Ridge with respect to the Nicaraguan Plateau has been approximately 200 km.

TECTONIC HISTORY

A number of tectonic conclusions can be made from the data presented. The Cayman Ridge and Nicaraguan Plateau are composed of complex assemblages of island arc-type plutonics and volcanics with genetically associated clastics and carbonates at least as old as Late Cretaceous. The Nicaraguan Plateau has a post-Eocene stratigraphy (i.e., history) that differs slightly from that of the Cayman Ridge. The rocks dredged reveal a complex stratigraphy that is correlative with the stratigraphy in northern Central America and the Greater Antilles. The mid-Cayman spreading center is composed of oceanic crustal rocks that have been formed at an active accreting plate margin.

One of the remaining problems in Caribbean geology has been the relationship between nuclear Central America and the younger, Greater Antilles. The geology of the Cayman Trench provides the missing link between these two regions and suggests a new model for the evolution of the northern boundary of the Caribbean Plate since the Cretaceous. Most Mesozoic pre-drift reconstructions require

the geologically unreasonable overlap of pre-Jurassic Central American crustal elements (Le Pichon and Fox, 1971). Thus, extensive reorganization of older Central America and the creation of most of the Caribbean crust between Early-Jurassic and Late-Cretaceous is implied. The Late Cretaceous to Recent development of the Caribbean plate is reflected in the relative motions between the North and South America Plates (Ladd, 1976). However, the pre-Cretaceous nature of the northern Caribbean can be speculated on only by investigating Paleozoic to Mesozoic stratigraphic and tectonic relations in Central America and Cuba.

The presence of a sub-linear chain of Late Paleozoic to Mesozoic granitic plutons and coeval volcanics in the northern Sierras in Guatemala and Maya Mountains in British Honduras suggests that oceanic crust was subducted northward beneath northern Central America prior to the Middle Mesozoic. To the south, were the parts of Paleozoic nuclear Central America that presently comprise the basement of southern Guatemala, Honduras and Nicaragua. Crustal thicknesses, regional geology and data presented here strongly suggest that the Cayman Ridge and Nicaraguan Rise were a single unit that extended east of the present Honduras coast prior to the Cretaceous.

In the Mid to Late Mesozoic, northward subduction gave way to left-lateral strike-slip faulting along the ancient Motagua-Polochic fault zone. A displacement of up to 1000 km has been indicated by the tentative correlation of Late Jurassic-Early Cretaceous evaporite sequences on the Yucatan Platform with salt diapirs presently found off the coast of Honduras (Pinet, 1972).

Others suggest major displacements of Paleozoic basement and Pre-Cretaceous units since the Cretaceous (Malfait and Dinkleman, 1972; Holcombe and others, 1973; Silver, 1974).

This fault zone was also the locus of submarine volcanism and eugeosynclinal sedimentation throughout the Cretaceous. Relative plate motions changed in the Early Cretaceous about 127 to 84 m.y. ago, as South America began to rotate counter clockwise with respect to North America (Ladd, 1974, 1976). This event caused compression at the northern plate boundaries which led to southerly subduction of oceanic lithosphere beneath ancestral southern Guatemala, Honduras, Nicaragua and the Nicaraguan Plateau-Cayman Ridge (Fig. 10a). Subsequently, a broad emergent volcanic arc developed above the Benioff Zone that extended from western Central America to Hispaniola. This chain of volcanic islands, surrounded by shallow-water carbonates and coarse clastics, is presently represented by the Cretaceous rocks from the Cayman Ridge, Nicaraguan Plateau, Jamaica, southern Cuba and western Hispaniola.

The subduction of Atlantic oceanic crust to the south or southwest beneath the Caribbean plate led to the development of somewhat older Laramide volcano-plutonic complexes in Cuba, eastern Hispaniola and Puerto Rico. Subduction north of Cuba probably terminated in the Late Cretaceous (around 87-82 m.y.b.p.) after the collision of Cuba and the Bahama Platform (Mattson, 1973). About this time, the Central American-Antillean subduction zone may have joined with the Atlantic (ancestral Puerto Rico) Trench. This eliminates the

need for a trench-trench transform along the Beata Ridge and the eastward stepping of a transform fault between the North American and Caribbean plates as Malfait and Dinkleman (1972) suggest.

At the end of the Cretaceous, remnants of the subducting oceanic crust were trapped between converging plates and consequently thrust onto the continents and islands. Associated serpentinites, basic schists and phiolitic rocks, of Late Cretaceous age, that outcrop in the Motagua Fault Zone, on the Bay Islands, in the Blue Mountains, Jamaica and along the Cauto Fault Zone in southeastern Cuba, were emplaced during this event. A similar compressional event occurred in the ancestral Puerto Rico Trench, that presently extends into northern Hispaniola, at the Cretaceous-Paleocene boundary (Perfit and others, 1974b). Closure of subduction zones and the onset of relative eastward movement of the Caribbean plate caused diminished volcanic activity in the Greater Antilles and Central America in the Early Tertiary. Southward movement of South America relative to North America caused extension along plate boundaries and zones of crustal weakness which led to the creation of tensional features such as the Motagua Valley in Guatemala, Cauto Basin in Cuba, Enriquillo-Cul de Sac Trough in Hispaniola, Wagwater Trough in Jamaica and the proto-Cayman Trench. These grabens were the locus of thick accumulations of erosional detritus from the still emergent volcanic islands (Fig. 10b). As volcanism and plutonism declined, vertical tectonics became more significant, probably due to the cessation of subduction, which caused cooling of the plate and subsequent isostatic readjustments. Locally, subsidence may have been rapid and great as

exemplified by nearly 20,000 feet of coarse Eocene sediment that filled the Wagwater Trough in Jamaica.

A number of facts lead us to believe that the creation of the present Cayman Trench began in the Eocene. Similar Early Tertiary estimates have been proposed by Ewing and others (1960), Bowin (1968), Malfait and Dinkleman (1972, Pinet (1972), Erickson and others (1972) and Holcombe and others (1973). Lateral movements may not have been localized along the present trench but rather were distributed among numerous sub-parallel faults that bisected the islands (Fig. 10b). Left-lateral shear between the North American and Caribbean plates is presently accommodated by transform faulting along fracture zones associated with the mid-Cayman spreading center, but it is not clear exactly when or how this accreting plate boundary developed. Pre-Eocene rocks from the trench walls and Cretaceous granodiorites from within the eastern trench show a significant amount of shearing, cataclasis and green-schist grade metamorphism that may be related to initial strike-slip motion along the trench. The spreading center probably formed in response to continued plate divergence and may be analogous to spreading in "leaky" fracture zones (Ranalli, 1974). As the spreading center developed, the trench became wider, lateral faulting was localized along the trench walls and denser oceanic crust was created on the floor. As a consequence of this, the Cayman Ridge and southeastern Cuba were rifted from the volcanic arc that included Hispaniola, Jamaica and the Nicaraguan Plateau (Fig. 10c). Similarly, the Beata Ridge may have rifted southward

from the southern flank of the Nicaraguan Plateau (Arden, 1975). Crustal accretion along the mid-Cayman spreading center at a rate of approximately .4 cm/yr offset these areas (left-laterally) since the Eocene. A total of about 200 km of left-lateral displacement between similar geologic features can presently be seen when comparing the Cayman Ridge and Nicaraguan Plateau. Laramide orogenic features in eastern Cuba and Hispaniola also suggest approximately 180 km of left-lateral movement since the Eocene (Malfait and Dinkleman, 1972). Recent left-lateral trans-current faulting has been evidenced by recent earthquakes and offsets up to 59 meters in stream and terrace deposits across the Motagua Valley (Schwartz, 1976).

Extensive vertical tectonics and regional subsidence occurred after the Eocene. Shallow-water carbonate shelf and reef environments covered those areas that were not uplifted in the final pulses of the Laramide Orogeny in the Late Eocene and Oligocene. The Cayman Ridge was predominantly a shallow carbonate bank until the Miocene when it began to subside. Banks and reefs were progressively restricted to a few isolated pinnacles on top of the Cayman Ridge. The Nicaraguan Plateau apparently had a more complex history of submergence, localized uplift, faulting and minor volcanism in the Mid-Tertiary but finally sank to its present depth by the Pliocene. Late Cretaceous-Paleocene granodiorites that may have been subaerially exposed in the Late Paleocene-Early Eocene, now outcrop at approximately 4000 meters on the Cayman Ridge, and Eocene and Oligocene shallow-water carbonates that generally outcrop below 3000 meters on both sides of the Cayman

Trench indicate subsidence rates of over 6 cm/1000 yrs. along the northern Caribbean margin. The Aves and Beata Ridges have subsidence histories nearly identical to those of the Cayman Ridge and Nicaraguan Plateau (Fox and others, 1971; Fox and Heezen, 1975).

After the mid-Miocene, localized uplift continued to elevate Central America and raised the Swan Islands, Cayman Islands, Jamaica and most of southern Cuba above sea level, while the surrounding crust continued to fault and subside. Decoupling of the Caribbean and Pacific plates along the Middle Americas Trench and descending isotherms beneath the Caribbean plate could explain the regional subsidence since the mid-Tertiary.

REFERENCES CITED

- Anderson, O. and Liebermann, 1968, Sound velocities in rocks and minerals; experimental methods, extrapolation to very high pressures and results, in *Physical Acoustics*, 4B Mason, W. P. (ed.), Academic, New York, p. 330-472.
- Arden, D. D., Jr., 1969, Geologic history of the Nicaraguan Rise; *Transactions - Gulf Coast Assoc. of Geol. Soc.*, v. 19, p. 295-309.
- Arden, D. D., Jr., 1975, The geology of Jamaica and the Nicaraguan Rise. in Nairn, A.E.M., and Stehli, F. (eds.), *The Ocean Basins and Margins*, v. 3, Plenum Press, New York.
- Banks, N. G., and Richards, M. L., 1969, Structure and bathymetry of western end of Bartlett Trough, Caribbean Sea: *Am. Assoc. Petroleum Geologists Mem.* 11, p. 221-228.
- Birch, F., 1961, The velocity of compressional waves in rocks to 10 kilobars, Part 2: *Jour. Geophys. Research*, v. 66, no. 7, p. 2199-2224.
- Bowin, C. O., 1968, Geophysical study of the Cayman Trough: *Jour. Geophys. Research*, v. 73, p. 5159-5175.
- Bowin, C. O., 1976, The Caribbean: Gravity Field and Plate Tectonics: *Geol. Soc. Amer. Spec. Paper* 169, (in press).
- Chubb, L. J., and Burke, K., 1963, Age of the Jamaican Granodiorite: *Geol. Mag.*, v. 100, p. 524-532.
- Dengo, G., 1969, Problems of tectonic relations between Central America and the Caribbean: *Gulf Coast Assoc. Geol. Socs. Trans.*, v. 19, p. 311-320.
- Dengo, G., and Bohnenberger, O., 1969, Structural development of northern Central America: *Am. Assoc. Petroleum Geologists Mem.* 11, p. 203-220.

- Dillon, W. P., Vedder, J. G., and Graf, R. J., 1972, Structural profile of the Northwestern Caribbean: *Earth and Planetary Sci. Letters*, v. 17, p 175-180.
- Dillon, W. P. and Vedder, J. G., 1973, Structure and development of the continental margin of British Honduras: *Geol. Soc. America Bull.*, v. 84, p. 2713-2732.
- Donnelly, T. W., Crane, D., and Burkart, B., 1968, Geologic history of the landward extension of the Bartlet Trough - some preliminary notes: *4th Caribbean Geol. Conf. Proc.*, Trinidad, p. 225-228.
- Edgar, N. T., Ewing, J. I. and Hennion, J., 1971, Seismic refraction and reflection in the Caribbean Sea: *Am. Assoc. Petroleum Geologists Bull.*, v. 55, p. 833-870.
- Eggler, D. H., Fahlquist, D. A., Pequegnat, W. E. and Herndon, J. M., 1973, Ultrabasics rocks from the Cayman Trough, Caribbean Sea: *Geol. Soc. America Bull.*, v. 84, p. 2133-2138.
- Erickson, A. J., Helsley, C. E. and Simmons, G., 1972, Heat flow and continuous seismic profiles in the Cayman Trough and Yucatan Basin: *Geol. Soc. America Bull.*, v. 83, p. 1241-1260.
- Ewing, J. and Ewing, M., 1959, Seismic refraction profiles in the Atlantic Ocean basins, Mediterranean Sea, Mid-Atlantic Ridge, and Norwegian Sea: *Geol. Soc. America Bull.*, v. 70, p. 291-318.
- Ewing, J., Antoine, J. and Ewing, M., 1960 Geophysical measurements in the western Caribbean Sea and in the Gulf of Mexico: *Jour. Geophys. Research*, V. 65, p. 4087-7126.

- Fahlquist, D. A., and Davies, D. K., 1971, Fault-block origin of the Western Cayman Ridge, Caribbean Sea: Deep-Sea Research, v. 18, p. 243-253.
- Fisher, R. V., 1961, proposed classification of volcanoclastic sediments and rocks: Geol. Soc. America Bull., v. 72, p. 1409-1414.
- Fox, P. J. and Heezen, B. C., 1975, Geology of the Caribbean crust, in Nairn, A.E.M., and Stehli, F. (eds.), The Ocean Basins and Margins, v. 3, Plenum Press, New York.
- Fox, P. J. and Schreiber, E., 1970, Granodiorites from the Cayman Trough: Geol. Soc. America Abs. with Programs, Pt. 7 (Ann. Mtg.), p. 553
- Fox, P. J., Schreiber, E. and Heezen, B. C., 1971, The geology of the Caribbean crust: tertiary sediments, granitic and basic rocks from the Aves Ridge: Tectonophysics, v. 12, p. 89-109.
- Fox, P. J., Schreiber, E. and Peterson, J. J., 1973, The geology of the Oceanic Crust: compressional wave velocities of oceanic rocks: Jour. Geophys. Research, v. 78, no. 23, p. 5155-5172.
- Gough, D. V., and Heirtzler, J. R., 1969, Magnetic anomalies and tectonics in the Cayman Trough: Geophys. Jour. Roy. Astr. Soc., v. 10, p. 33-49.
- Green, G. W., 1972, The geology of the Wagwater Belt, Jamaica: 6th Caribbean Geol. Conf., Venezuela, p. 131.
- Harland, W. B., Smith, A. G. and Wilcock, B., eds., 1964, The Phanerozoic time-scale: Geol. Soc. London Quart. Jour., v. 120, 458 p.

- Hatten, C. W., and Meyerhoff, A. A., 1970, The Caribbean area:
a case of destruction and regeneration of a continent:
Discussion: Geol. Soc. America Bull., v. 81, p. 1855-1862.
- Hill, M. N., 1957, Recent geophysical exploration of the ocean
floor: Progr. Phys. Chem. Earth, v. 2., p. 129-163.
- Holcombe, T. L., Vogt, P. R., Matthews, J. E. and Murchison,
R. R., 1975, Evidence for sea-floor spreading in the Cayman
Trough: Earth and Planetary Sci. Letters, v. 20, p. 357-371.
- Horne, G. S., Pushkar, P., and Shafigullah, M., 1974, Laramide
plutons on the landward continuance of the Bonacca Ridge,
Northern Honduras: VII eme Conf. Geol. des Caraibes, Antilles.
- Iturralde-Vincent, M. A., 1975, Problems in application of modern
tectonic hypotheses to Cuba and Caribbean region: Am. Assoc.
Petroleum Geologists, v. 59, no. 5, p. 838-855.
- Jordan, T. H., 1975, The present-day motions of the Caribbean
Plate: Jour. Geophys. Research, v. 80, p. 4433-4440.
- Kartashov, I. P. and Mayo, N. A., 1972, Principales rasgos del
desarrollo geologics de Cuba Oriental en el Cenozoico tardio:
6th Caribbean Geol. Conf., p. 108-111.
- Kesler, S. E., 1971, Nature of ancestral orogenic zone in nuclear
Central America. Am. Assoc. Petroleum Geologists, v. 55,
p. 2116-2129.
- Khudoley, K. M. and Meyerhoff, A. A., 1971, Paleogeography and
geological history of the Greater Antilles: Geol. Soc.
America Mem. 129, 199 p.

- Ladd, J. W., 1974, South Atlantic sea-floor spreading and Caribbean tectonics, unpublished Ph.D. dissertation, New York, Columbia University, 250 p.
- Ladd, J. W., 1976, Relative motion of South America with respect to North America and Caribbean tectonics, Geol. Soc. Amer. Bull., v. 87, p. 969-976.
- Langseth, M. G. and Von Herzen, R. P., 1971, Heat flow through the floor of the world oceans, in The Sea, Maxwell, A. E., (ed.) v. 4, Wiley-Interscience, New York, p. 299-352.
- Lawrence, D. P., 1975, Petrology and structural geology of the Sanarate-El Progreso Area, Guatemala: unpublished Ph. D. dissertation, S.U.N.Y., Binghamton.
- Le Pichon X. and Fox, P. J., 1971, marginal offsets, fracture zones and the early opening of the North Atlantic, Jour. Geophys. Res., v. 76, p. 6244-6308.
- Lewis, J. F., Harper, C. T., Kemp, A. W., Stipp, J. J., 1973, Potassium-Argon retention ages of some cretaceous rocks from Jamaica: Geol. Soc. America Bull., v. 84, p. 335-340.
- MacDonald, W. D. and Melson, W. G., 1969, A Late Cenozoic volcanic province in Hispaniola: Carib. J. Sci., v. 9., p. 81-91.
- Malfait, B. T. and Dinkleman, M. J., 1972, Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean plate: Geol. Soc. America Bull., v. 83, p. 251-272.
- Malin, P. E. and Dillon, W. p., 1973, Geophysical reconnaissance of the western Cayman Ridge: Jour. Geophys. Research, v. 78, p. 7769-7775

- Matthews, J. E., 1974, The geomagnetic field of the Caribbean Sea: Geol. Soc. America Abs. with Programs, v. 6, No. 7, p. 859.
- Mattson, P.H., 1973, Cuba, in Spencer A.M. (ed.), Mesozoic-Cenezoic Orogenic Belts: Data for orogenic studies: Geol. Soc. London, Spec. Publications, p. 625-638.
- Mattson, P. H., 1974, Mesozoic and Tertiary lithospheric plate interactions in the northern Caribbean: VII eme Conf. Geol. des Caraibes, Antilles.
- McBirney, A. R. and Williams, H., 1965, Volcanic history of Nicaragua: California Univ. Public. Geol. Sci., v. 55, p. 1-65.
- McBirney, A. R. and Bass, M. N., 1969a, Geology of Bay Islands, Gulf of Honduras: Am. Assoc. Petroleum Geologists, Mem. 11, p. 229-243.
- McBirney, A. R., 1969b, Structural relations of pre-Mesozoic rocks of northern Central America: Amer. Assoc. Petroleum Geologists, Mem. 11, p. 269-280.
- Meyerhoff, A. A., 1966, Bartlett fault system: age and offset: Trans. 3rd Carib. Conf., p. 1-9.
- Mills, R. A., Hugh, K. E., Feray, D. E. and Swolfs, H. C., 1967, Mesozoic stratigraphy of Honduras: Am. Assoc. Petroleum Geologists, v. 51, no. 9, p. 1711-1786.
- Molnar, P. and Sykes, L. R. 1969, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity: Geol. Soc. Amer. Bull., v. 80, p. 1639-1664.
- Muehlberger, N. R. and Richie, A. W., 1975, Caribbean-America plate boundary in Guatemala and southern Mexico as seen in Skylab IV orbital photography: Geology, v. 3, p. 232-235.

- Newcomb, W. E., 1975, Geology, structure and metamorphism of the Chuacus group, Rio Hondo Quadrangle and vicinity, Guatemala: Ph.D. dissertation (unpublished). S.U.N.Y., Binghamton.
- Pardo, G., 1975, Geology of Cuba, In Nairn, A.E.M., and Stehli, F. (eds.), The Ocean Basins and Margins, v. 3, Plenum Press, New York.
- Perfit, M. R., Kay, R., Heezen, B. C., 1974, Petrologic Evidence for Sea-Floor Spreading in the Cayman Trench, Geol. Soc. Amer. Abs. w. programs, v. 6, No. 7, p. 908.
- Perfit, M. R., Heezen, B. C. and Catalano, R., 1974b, Metamorphic rocks from the Puerto Rico trench: Geol. Soc. America Abs. w. programs, v. 6, no. 7, p. 907-908.
- Perfit, M. R., 1977, Petrology and geochemistry of mafic rocks from the Cayman Trench: evidence for spreading; Geology, v. 5, p. 105-110.
- Pettijohn, F. J., Potter, P. E. and Siever, R., 1973, in Sand and sandstone: New York, Springer-Verlag, 618 p.
- Pinet, P. R., 1972, Diapirlike features offshore Honduras: implications regarding tectonic evolution of Cayman Trough and Central America: Geol. Soc. Amer. Bull., v. 83, p. 1911-1922.
- Pinet, P. R., 1975, Structural evolution of the Honduras continental margin and the sea floor south of the western Cayman Trough: Geol. Soc. Amer. Bull., v. 86, p. 830-838.
- Raitt, R. W., 1963, The crustal rocks, in The Sea, v. 3., Hill, M. N., ed., New York, John Wiley, p. 85-102.
- Ranalli, G., 1974, Tectonic role of oceanic fracture zones: Marine Geol., v. 17, p. M27-M34.

- Roobol, M. J., 1972, The volcanic geology of Jamaica: 6th Caribbean Geol. Conf., p. 100-107.
- Schuchert, C., 1935, Historical Geology of the Antillean-Caribbean Region: New York, John Wiley and Sons, 811 p.
- Schwartz, D. P., and Newcomb, W. E., 1973, Motagua Fault Zone: a crustal structure: AGU Transactions, E.O.S., V54, p. 477.
- Schwartz, D. P., 1976, Petrology and structural geology of the Zaccapa-Rio Hondo Area, Guatemala: unpublished Ph.D. dissertation, S.U.N.Y., Binghamton.
- Silver, E. Z., 1974, Late Cenozoic plate tectonics of the Caribbean region: Geol. Soc. America Abs. with programs, v. 6, no. 7, p. 957.
- Skvor, V., 1969, The Caribbean area: a case of destruction and regeneration of the continent: Geol. Soc. America Bull., v. 80, p. 961-968.
- Sykes, L. R., and Ewing, M., 1965, The seismicity of the Caribbean region: Jour. Geophys. Research, v. 70, p. 5065-5070.
- Vedder, J. G., MacLeod, N. S., Lanphere, M. A. and Dillon, W. P., 1973, Age and tectonic implications of some low grade metamorphic rocks from the Yucatan Channel: U. S. Geol. Surv. J. Res., v. 1, p. 157-164.
- Walper, J. L., and Rowett, C. L., 1972, Plate tectonics and the origins of the Caribbean Sea and the Gulf of Mexico: Gulf Coast Assoc. of Geol. Soc. Transactions, v. 22, p. 105-116.
- Williams, H. and McBirney, A. R., 1969, Volcanic history of Honduras: California Univ. Pubs. Geol. Sci., v. 85, p. 1-101.

- Wilson, H. H., 1974, Cretaceous sedimentation and orogeny in nuclear Central America: Am. Assoc. Petroleum Geologists, v. 58, p. 1348-1396.
- Wright, R. M. and Dickinson, W. R., 1972, Provenance of Eocene volcanic sandstones in eastern Jamaica - a preliminary note: Carib. J. Sco., v. 12, p. 107-113.
- Zans, V. A., Chubb, L. J., Versey, H. R., Williams. Y. B., Robinson, E. and Cooke, D. L., 1962, Synopsis of the geology of Jamaica: Geol. Sur. Dept., Jamaica, Bull. 4, 72 p.

TABLE 1. K-Ar DIOMETRIC AGES

No.	Station No.	Sample I.D.	Rock Type	^{40}Ar / ^{39}Ar x 10 ⁻⁵		^{40}Ar Rad %	%K	Isotopic Age (m.y.)
				scc				
1	4	E438-1	Tonalite	0.198		22	0.58	83 $\pm$ 2
2	32	E1091-C	Granodiorite	0.637		75	2.46	64 $\pm$ 10
3	39	E1098-1	Granodiorite	0.364		33	1.52	59 $\pm$ 3
4	40	E1099-1	Granodiorite	0.463		75	1.89	60 $\pm$ 3
5	40	E1099-4	Amphibolite	0.246		50	0.87	69 $\pm$ 9
6*	32	1091	Granodiorite					
			feldspar	..		..	..	59.2 $\pm$ 1.2
			biotite	..		..	..	59.3 $\pm$ 1.2
			hornblende	..		..	..	58.6 $\pm$ 8.8
7*	37	1096	Granodiorite					
			feldspar	..		..	..	59.4 $\pm$ 1.4
			feldspar	..		..	..	60.2 $\pm$ 1.2

Constants used: $\lambda_B = 4.72 \times 10^{-10} \text{yr}^{-1}$; $\lambda_e = 0.585 \times 10^{-10} \text{yr}^{-1}$; $K^{40} = 1.19 \times 10^{-4}$ atom percent of natural potassium.

Analyses done by Teledyne Isotopes, New Jersey.

*Analyses done by R.E. Denison Mobile Research, Dallas, Texas.

FIGURE CAPTIONS

- Figure 1. Index map of Cayman Trench showing major morpho-tectonic units. Outlined area is field of view in Figure 2.
- Figure 2. Bathymetric map of Cayman Trench modified from Holcombe and others, (1973). Location of successful dredge stations indicated by solid circles; numbers correspond to station numbers listed in text. R. V. CONRAD seismic reflection profile traverse is labeled RC-12.
- Figure 3. Seismic reflection profile traversing the Cayman Ridge (CR), the floor of the trench, and the Nicaraguan Plateau (NP). Location of profile is in Figure 2. Notice the thick accumulation of sediment on top of the Cayman Ridge and Nicaraguan Plateau and the nearly sediment-free escarpments. The rugged morphology of the mid-Cayman spreading center and the shallow ponding of sediment between steep peaks is clearly shown in the center of the profile. Profile is from Columbia University's R. V. CONRAD.
- Figure 4. Diagrammatic representation of the geology of the Cayman Ridge and stratigraphy at each station (bold numbers). Cross sections have been projected forward onto a plane. Locations of each section are approximate to avoid overlap and to simplify presentation. All views are looking toward the north. The solid lined base of each section lies at the greatest depth of recovery but in order to represent each rock type recovered, the total height of a section may be exaggerated. Refer to the appendix and Figure 2 for exact locations, depths of recovery and rock descriptions. Small numbers are K-Ar dates referred

- Figure 4. (con't) to in text and on Table 1. Non-horizontal lines are not time-stratigraphic and represent possible interbedding of units, vertical tectonics and folding have not been accounted for. Small dots and lines in carbonates indicate clastic carbonates.
- Figure 5. Diagrammatic representation of the geology of the Nicaraguan Plateau. See Figure 4 for explanation and key.
- Figure 6. Diagrammatic representation of the stratigraphy and geology of the mid-Cayman spreading center. See Figure 4 for further explanation.
- Figure 7. Next page.
- Figure 8. Seismic refraction structure sections of the a) Cayman Trench region and b) eastern Cayman Trench south of Cuba, both from Ewing and others, (1960).
- Figure 9. Idealized geologic cross-sections of the Nicaraguan Plateau-Cayman Ridge and the mid-Cayman spreading center correlated with seismic sections of Ewing et al, (1960). Bold numbers over each seismic section refer to seismic lines in Ewing and others, (1960) and Figure 8. Compressional wave velocities of each layer are in km/sec. Velocities to the left of the idealized sections are estimated ranges for the designated rock types. Numbers in parentheses refer to specific rock types discussed in the text.
- Figure 10. Schematic drawings portraying the evolution of the northern Caribbean margin and Cayman Trench since the Late Cretaceous.

Figure 7

Photomicrographs Of Rocks From The Cayman Trench

Figure 7

- a) Lapilli tuff from the Cayman Ridge (station #22) composed of folded lapilli altered to chlorite in a clayey to microlitic groundmass. Plain light.
- b) Granodiorite from the Cayman Ridge (39) containing subhedral zoned plagioclase, hornblende, biotite and anhedral intergranular orthoclase and quartz. Cross-Nicols.
- c) Volcanic from the Cayman Ridge (42) subtrachytic with relict hornblende phenocrysts surrounded by opaques and embayed quartz in a microcrystalline felsic groundmass. Plain light.
- d) Dacite from the Cayman Ridge (42) containing large embayed quartz phenocrysts and smaller rounded sanidine in a perlitic groundmass. Minor subhedral hornblende and abundant opaques. Cross-Nicols.
- e) Quenched basalt from the mid-Cayman spreading center (78) containing feathery pyroxene and olivine, skeletal plagioclase. Plain light.
- f) Gabbro from the mid-Cayman spreading center (75) containing fractured plagioclase with bent twin lamellae, diallage pyroxene with hornblende alteration rim. Cross-Nicols.

Figure 10. Large arrows indicate relative motion between North American and South American Plates. Solid lines represent present land boundaries; broken lines are approximate regions of emergent land and shallow banks in the past.

a) Late Cretaceous, prior to the collision of Yucatan and Honduras-Nicaragua. NP-CR is the combined mass of the Nicaraguan Plateau and Cayman Ridge. J, C and H represent the approximate locations of Jamaica, Cuba and Hispaniola prior to left lateral movement along the Cayman Trench.

b) Pre-Oligocene, after subduction to the south ceases; left lateral motion begins along the Cayman Trench fault, accompanied by the formation of numerous tensional grabens. The Cayman Ridge (CR and Oriente Province (c) are split from the emergent arc to the south. Spreading is initiated in proto-Cayman Trench. Volcanism wanes along the Greater Antilles arc; and begins along the western coast of Central America (open triangles) due to subduction along the Middle Americas Trench.

c) Late Tertiary, continued relative left-lateral motion between North America and Caribbean plates; localization of left-lateral shearing and normal faulting along the walls of the Cayman Trench. Mafic floor of the trench is formed as spreading continues from the mid-Cayman spreading center. Extensive subsidence causes disappearance of Cayman Ridge and Nicaraguan Rise land masses; progressive restriction of carbonate banks. Oriente Province is sutured on to Cuba. Volcanism ceases in the Greater Antilles but increases in Western Central America as Middle Americas Trench extends Southeastward.

Fig 1.

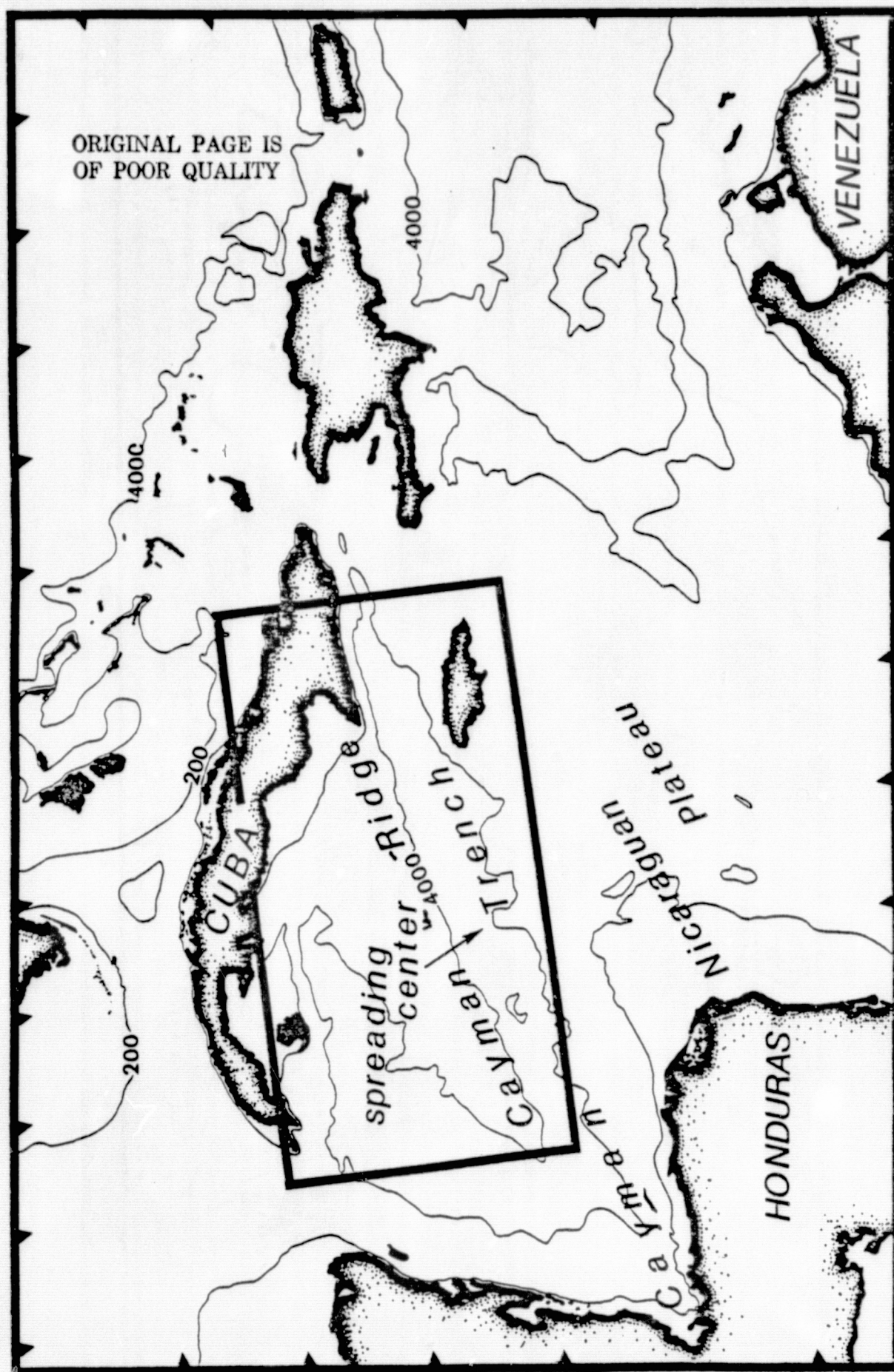
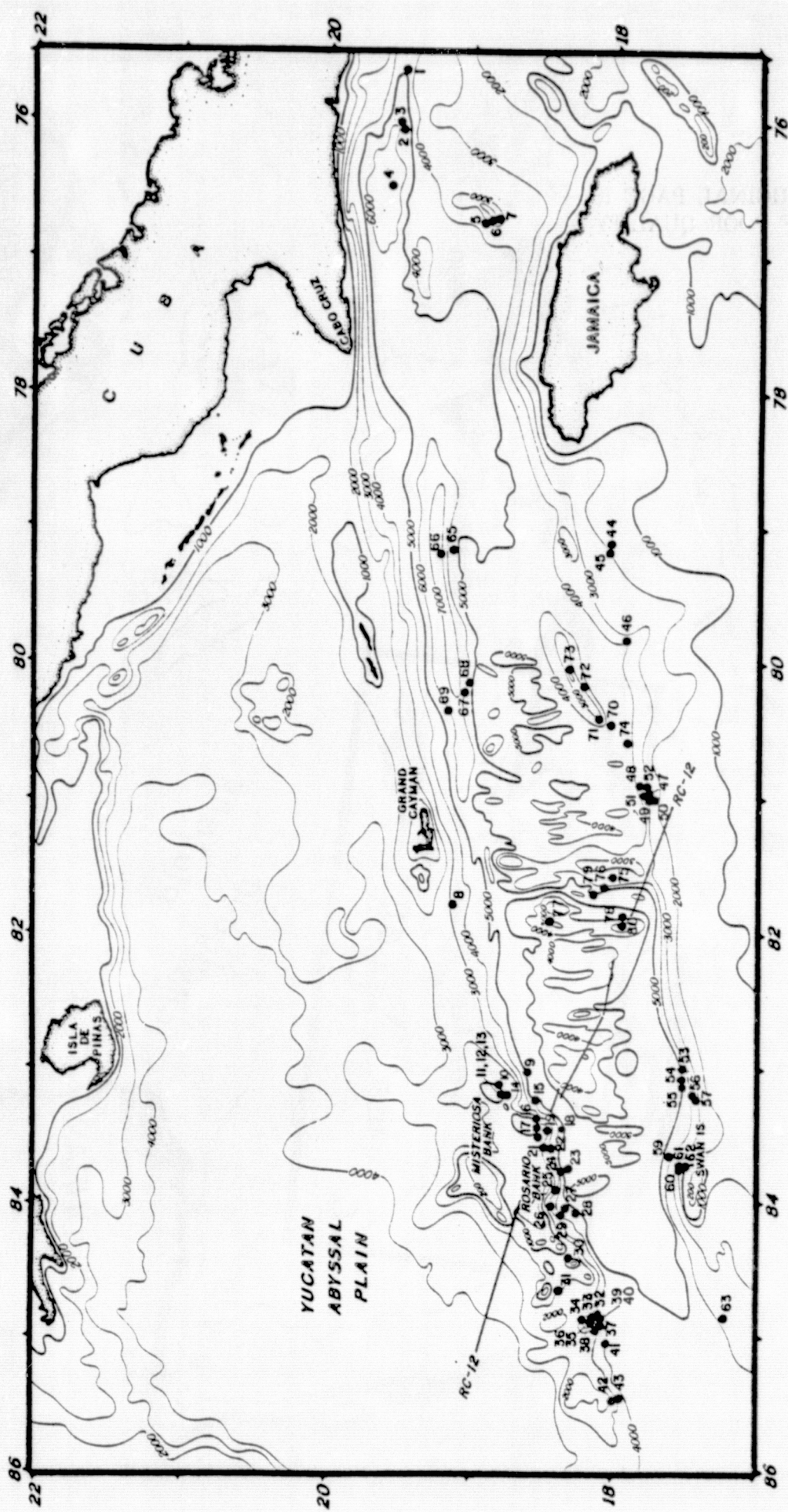


Fig. 2



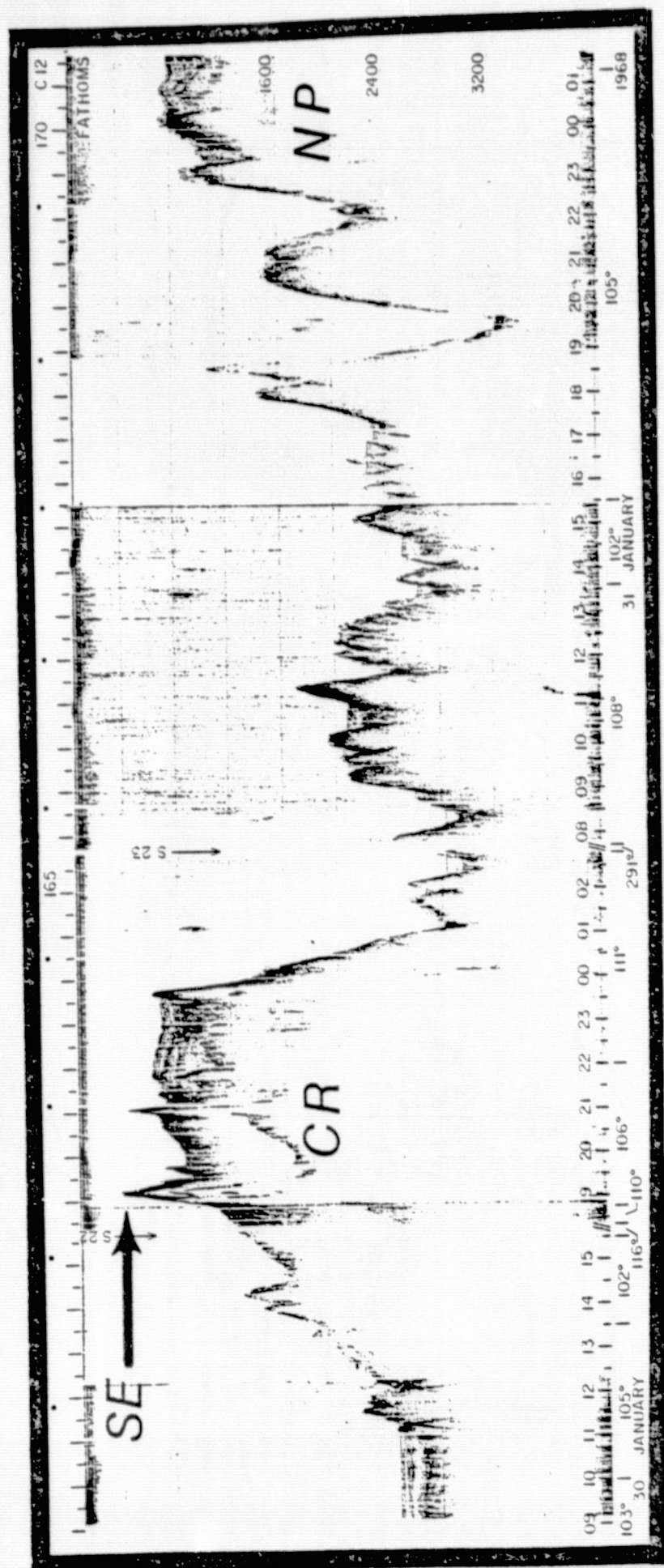
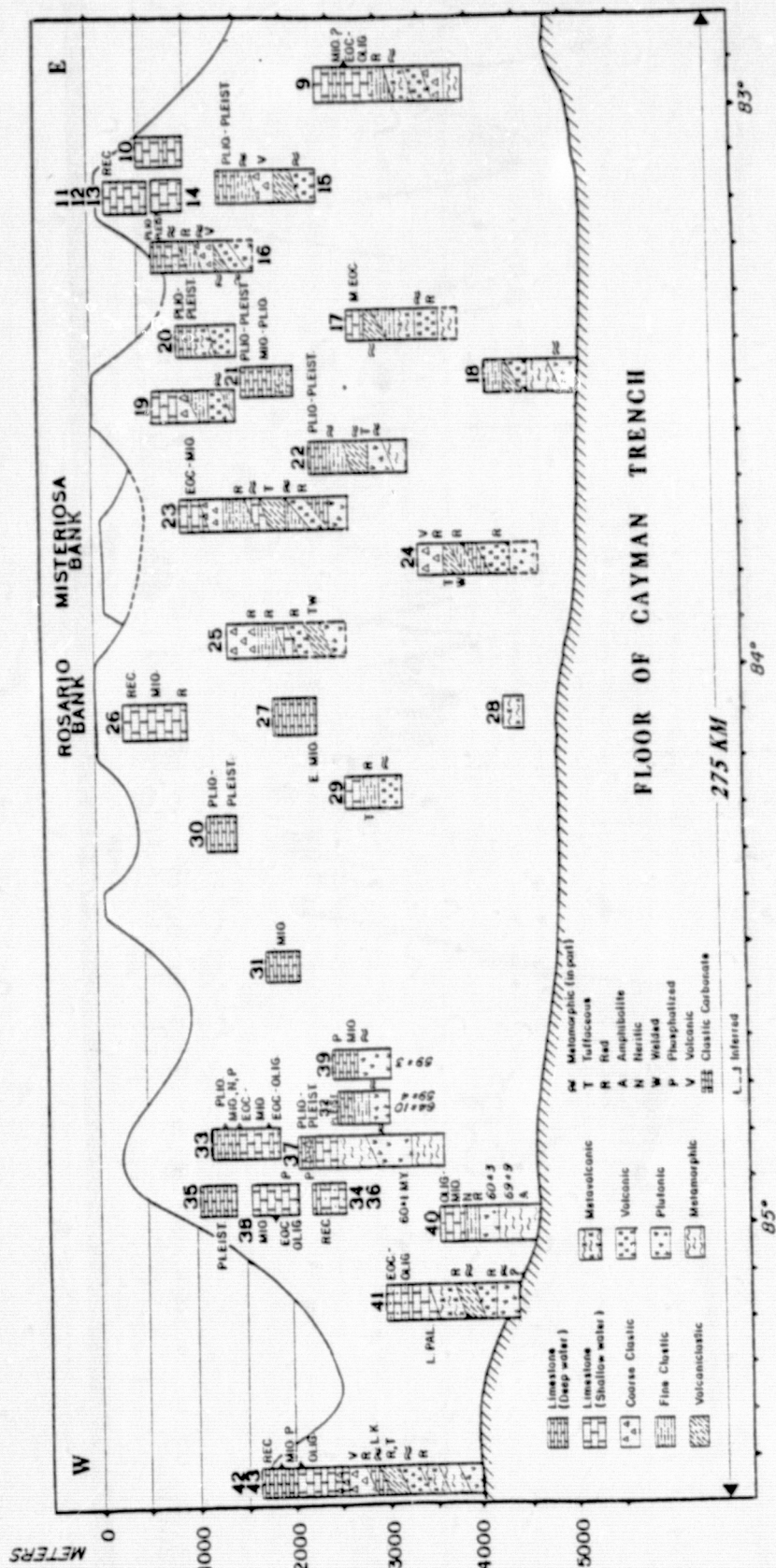
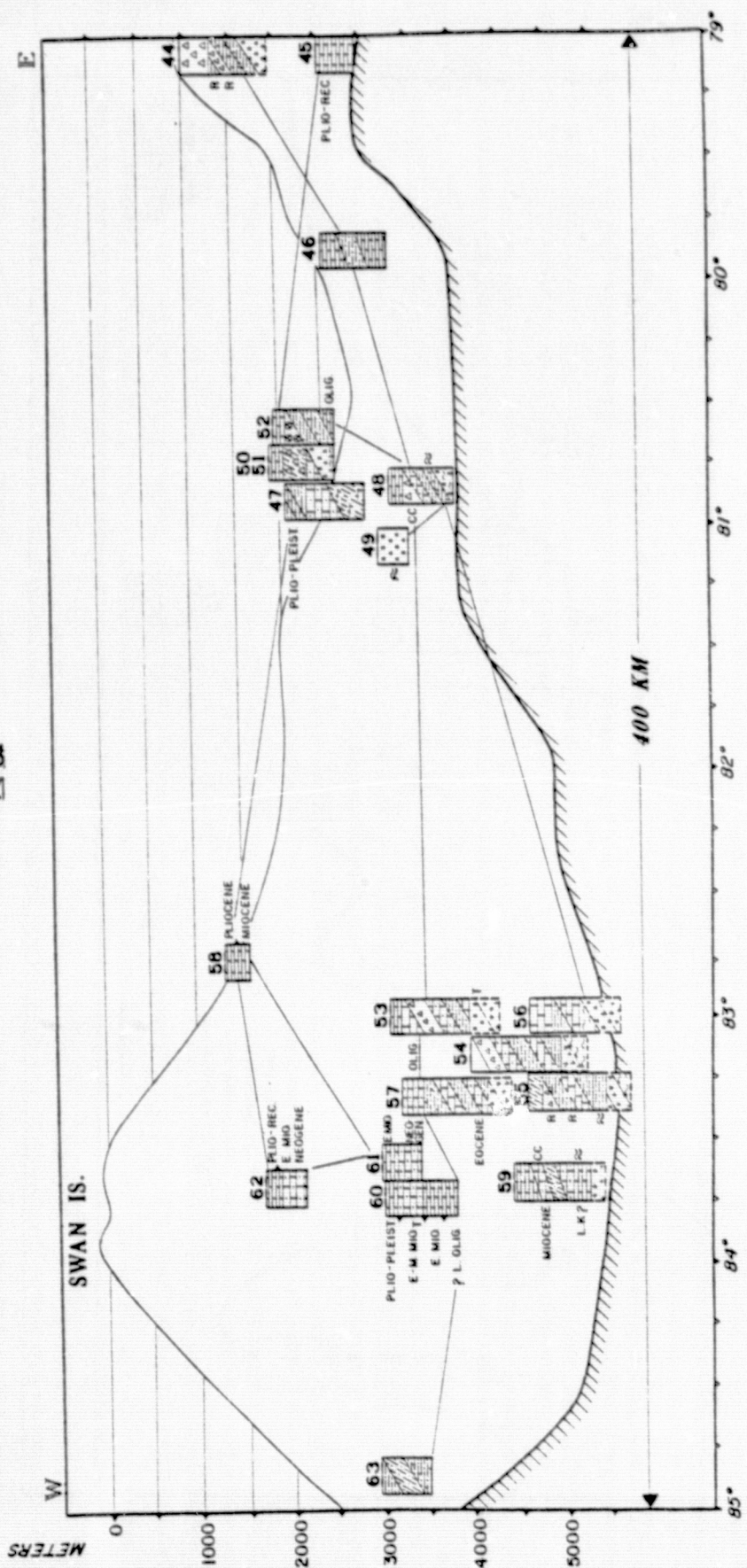


Fig 4.



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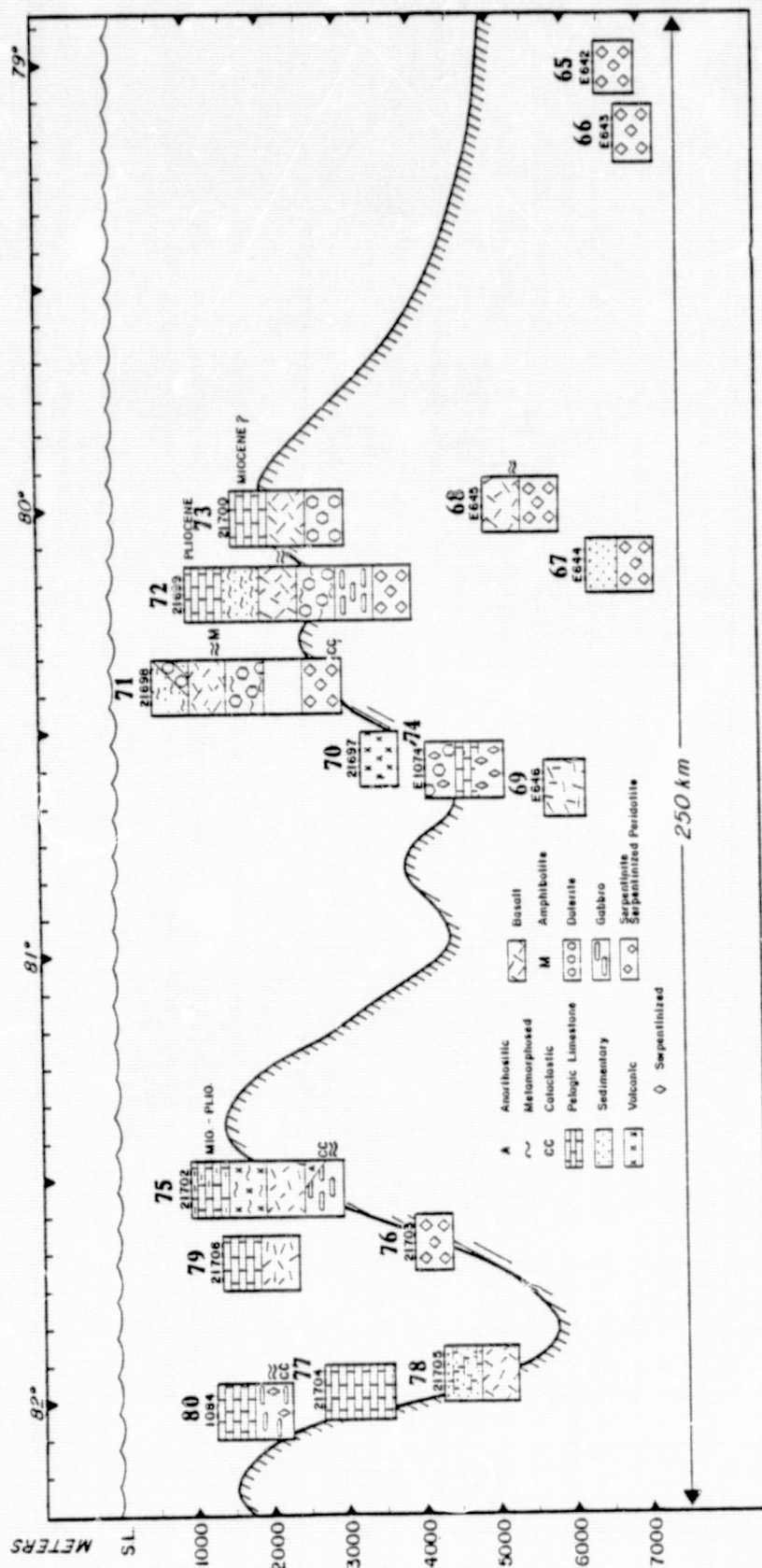


Fig 7

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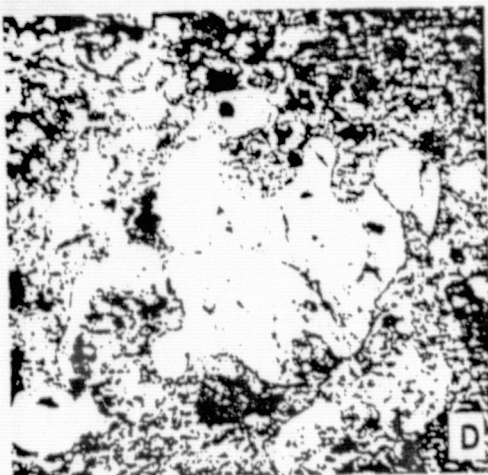
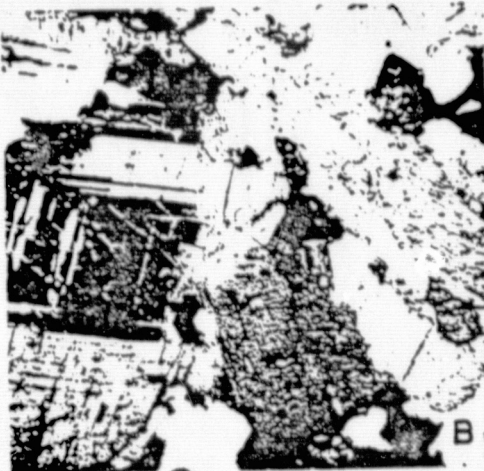
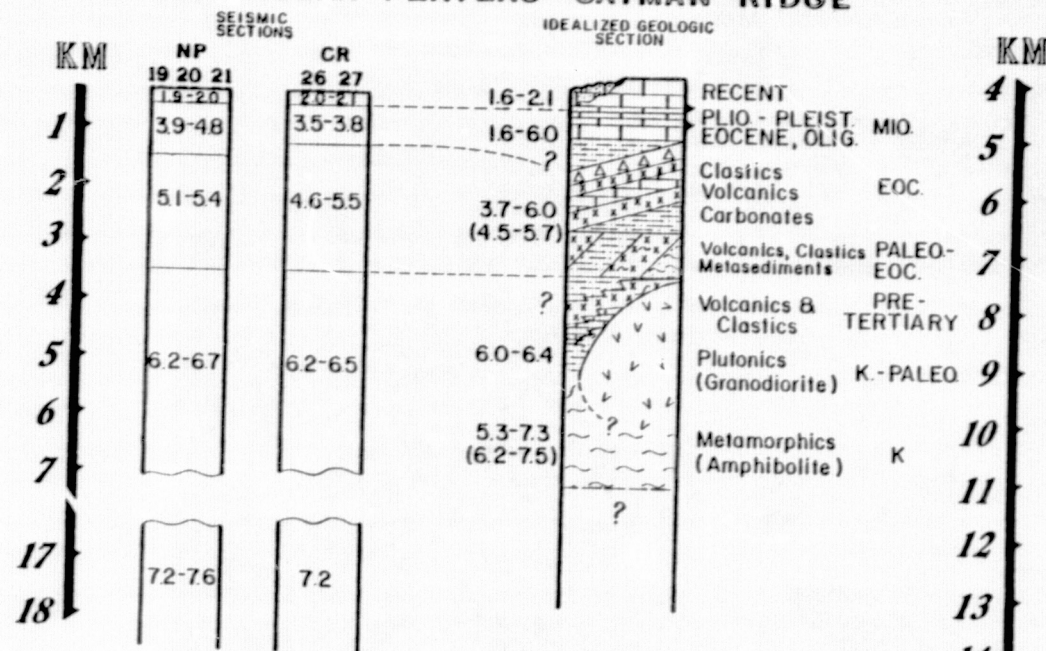


Fig 9

NICARAGUAN PLATEAU - CAYMAN RIDGE



MID-CAYMAN SPREADING CENTER

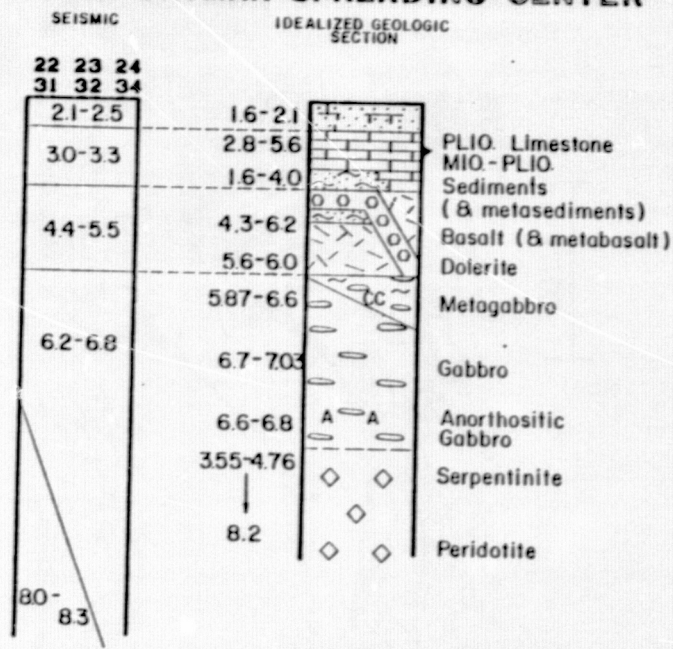
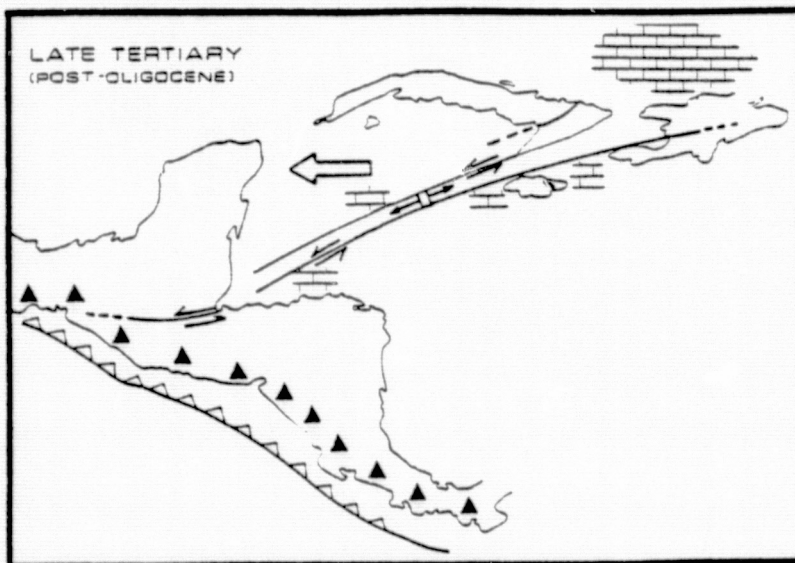
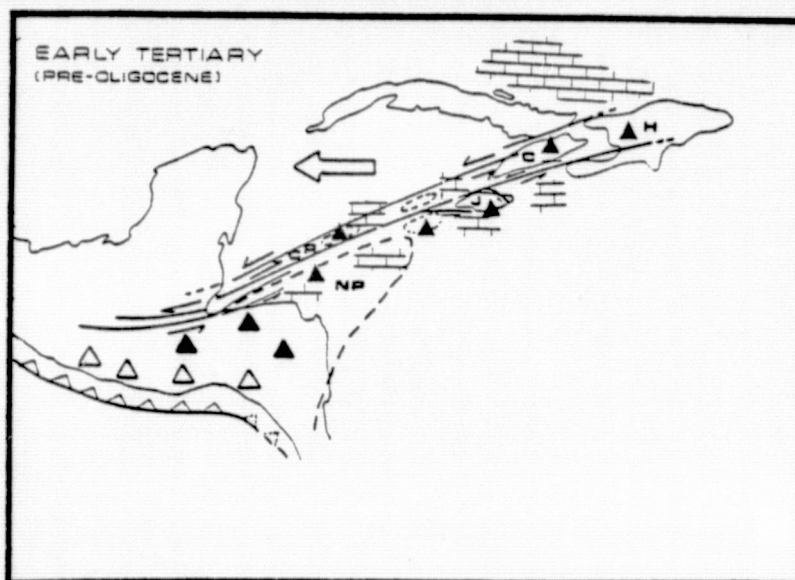
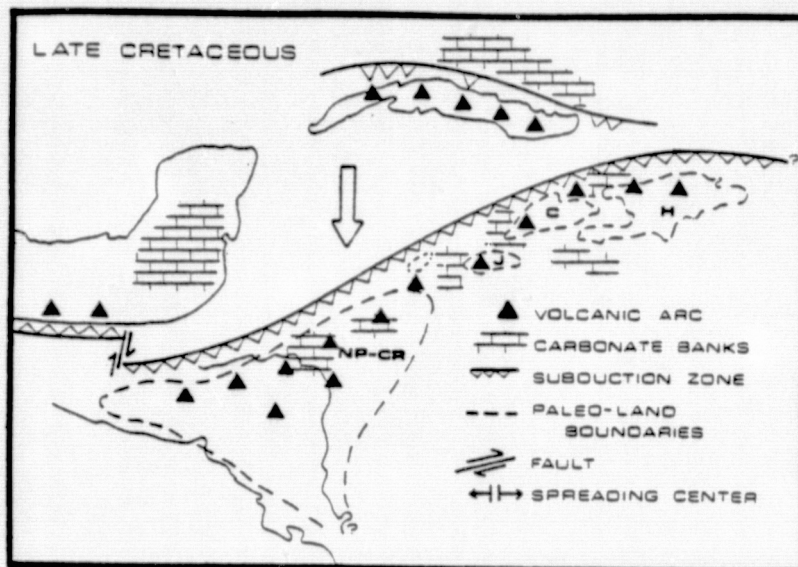


Fig 10



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Some petrological aspects of Imbrium stratigraphy†

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Petrochemical studies of clasts in breccias from Fra Mauro and Apennine Front provide insights into different structural levels of pre-Imbrium terra crust. Most of the Fra Mauro breccias and included clasts are 'kreep' basalts showing both igneous and cataclastic textures and are interpreted as the surface veneer of the terra crust. Similar samples were collected from the Apennine Front near Spur Crater, but they are mixed in with clasts of coarse, plutonic texture. One clast type is spinel pyroxenite whose mineralogy and petrochemistry are consistent with the original rock type being garnet pyroxenite. Such a mineral assemblage could only be stable at greater than 300 km depth, well within the lunar upper mantle. It is suggested that these clasts represent garnet pyroxenite xenoliths, emplaced within the lunar crust during early volcanism, that underwent a phase transition to spinel pyroxenite. Another clast type is plutonic norite, in which coarsely exsolved inverted pigeonite is associated with anorthitic plagioclase. Similar terrestrial rocks are found in Stillwater-type layered intrusions, and it is suggested that the lunar norites were parts of terra crustal layered complexes developed beneath a veneer of impact brecciated crust. Examples of the latter are illustrated by poikiloblastic-textured gabbroic anorthosite, with inverted pigeonite oikocrysts surrounding grains of plagioclase, augite, pigeonite, orthopyroxene, olivine and ilmenite. Application of mineral geothermometers indicates crystallization of these rocks below 1100 °C, temperatures that are well below the liquidus. Hence these textures probably developed largely by solid state recrystallization during impact-metamorphism.

INTRODUCTION

The depth of excavation of major lunar basins remains a contentious question. Extensive excavation of basins the size of Imbrium should have ejected samples of the lower lunar crust or possibly the upper mantle. We find no sample in the Imbrium ejecta at either the Apollo 14 or 15 site that can *unequivocally* be related to deep stratigraphic levels. This suggests that samples from Fra Mauro and the Apennine Front sampled relatively shallow crustal levels, although cratering studies indicate that Apennine Front samples would be from a *relatively* deeper level than those from the Fra Mauro site.

Attempts to reconstruct a pre-Imbrium stratigraphy for the upper terra crust, in even the most simplistic manner, are hampered by the lithologic complexity of the Imbrium breccias and thermal metamorphic overprinting. The most direct reflection of pre-Imbrium lithologies is provided by clasts in breccias. The clasts dominantly show fragmental textures, indicative of a terra crust already pervasively fragmented prior to the Imbrian event. Of the other clast types present at the Fra Mauro site, most have basaltic textures with very infrequent examples of coarse-grained rocks. The basaltic clasts are all 'kreep'-like in composition, as are most of the Fra Mauro samples, irrespective of texture. One might argue then that the Imbrium crust

† Lamont-Doherty Geological Observatory of Columbia University Contribution No. 2383.

had a veneer of creep basalt that was excavated to the Fra Mauro site during the Imbrian event. In comparison creep basalts are not so prevalent at the Apennine Front, although they are still major clast types in the terra breccias. In addition other clasts are present with coarse textures which suggest a plutonic environment of formation, consistent with a deeper level of excavation at the Apennine Front.

Following, are descriptions of the petrochemistry of two Apennine Front breccias 15445, 15459, both ejected to the surface during excavation of Spur Crater. Discussion centres on the relevance of the various components of the breccias to pre-Imbrium stratigraphy.

GLASS POPULATION

Breccia 15459 is a clast-laden, glass matrix breccia. The matrix contains numerous angular to spherical glass particles, which have been analysed by electron microprobe techniques. Average glass compositions and relative glass abundances are shown in table 1. Green glass with very little compositional variance dominated the glass population, as observed in several other Apollo 15 soils (Reid *et al.* 1972). Indeed the relative glass abundances for the breccia matrix are close to those estimated for soil samples collected near Spur Crater (table 1). Two

TABLE 1. AVERAGE GLASS COMPOSITIONS IN 15459 MATRIX

	1	2	3	4	5	6	7	8	9
SiO ₂	45.24	45.43	49.52	46.40	44.11	35.38	37.64	42.93	43.95
TiO ₂	0.34	0.42	1.37	0.85	0.05	13.64	12.04	3.11	2.79
Al ₂ O ₃	7.53	7.72	17.08	19.47	30.90	7.26	8.46	8.89	8.96
Cr ₂ O ₃	0.45	0.43	0.19	0.17	0.03	0.64	0.48	0.46	0.46
FeO	19.51	19.61	9.37	8.34	3.53	21.42	19.93	21.72	21.10
MgO	17.55	17.49	9.07	12.49	3.51	12.10	10.49	12.37	12.30
CaO	8.23	8.34	10.65	11.39	17.23	7.66	8.81	8.68	9.02
Na ₂ O	0.13	0.12	0.63	0.53	0.13	0.52	0.54	0.39	0.27
K ₂ O	0.01	~0.01	0.50	0.18	0.01	0.14	0.13	0.08	0.05
Total	98.98	99.57	98.38	99.82	99.49	98.76	98.52	98.63	98.90

1, Green glass. 2, Average green glass composition in three Apollo 15 soils (Reid *et al.* 1972). 3, Medium-K creep. 4, Low-K creep. 5, 'Anorthositic' component. 6, High-Ti mare basalt. 7, 'Mare 4' glasses in Apollo 15 soils (Reid *et al.* 1972). 8, Mare glasses. 9, 'Mare 3' glasses in Apollo 15 soils (Reid *et al.* 1972).

Average abundances:	15459	A-15 soil
Green glass	43%	34%
Low-K creep	13%	15%
Medium K creep	20%	22%
'Anorthosite'	2%	
Mare	22% (High-Ti 2%)	22%

types of aluminous basaltic glass were observed, one type termed medium-K creep (following the terminology of Reid *et al.* (1972)) and a second with lower K₂O, TiO₂ and higher Mg/Fe ratio, termed low-K creep. The latter is synonymous with the low-alkali basalt composition of Prinz *et al.* (1973) and is representative of a compositional group found at most lunar landing sites (Ridley *et al.* 1973). Unlike creep, samples of which have been described with unequivocal basaltic textures, low-K creep has only been described as a glass or clasts with hornfelsic textures. Hence the significance of this composition as a pristine basaltic magma remains ques-

tionable. Particularly disturbing is the observation that the polymict matrix of 15459 has a bulk composition of low-K creep, indicating that in at least one case, the composition arises by a mixture of several chemically distinct components.

The matrix also contains a high proportion of mare-like glasses, based upon their Fe/Mg ratio and TiO₂ content. Two types of mare glass have been distinguished, a high-Ti type (table 1), closely analogous to the 'Mare 4' glasses analysed from Apollo 15 soils (Reid *et al.* 1972), and a low-Ti type analogous to the 'Mare 3' glasses from Apollo 15 soil (Reid *et al.* 1972). This latter glass group is equivalent to the most magnesian olivine-normative mare basalt from Palus Putredinus (Rhodes & Hubbard 1973). No glasses were found equivalent to the Apollo 15 quartz-normative mare basalts. The high-Ti glasses (a minor component) have no basalt equivalent at the Apollo 15 site but have been observed at almost all Apollo landing sites (Reid *et al.* 1972). Chemically they are similar to, but somewhat more magnesian than, the olivine-normative Apollo 17 basalts.

An important point is the absence of glasses chemically equivalent to the 'highland basalt' or anorthositic gabbro component observed in abundance in most lunar soils, including those from the Apollo 15 site. Indeed the 'terra' component in 15459 glasses is of very minor importance, represented by only a few glasses of gabbroic anorthosite composition. This anachronism is the only major difference between glass abundances in the matrix of 15459 and Apennine Front soils.

Several observations can be made regarding the matrix data. The bulk composition of the matrix is similar to that of several Apennine Front soils. Together with the overall similarities in glass abundances in the matrix and soils, we might surmise that the breccia could have evolved by induration of a pre-existing local soil. From the individual, average glass compositions it is evident that green glass forms a dominant component in both Apennine Front soils and glass-laden breccias. The composition of green glass remains highly invariant, but its source still remains enigmatic. If the low-K creep composition is representative of a basalt magma-type then it should play an important role in lunar petrogenesis. For instance, in appropriate equilibrium systems it clusters around peritectic points and hence schemes can be evolved relating to creep magma and a spectrum of cumulate rocks, e.g. troctolites, norites, anorthosites. At present however, its rank as a magma type remains speculative.

PETROCHEMISTRY OF SELECTED CLASTS

(a) *Spinel-pyroxenite*

Ridley *et al.* (1973) have described a number of pink-spinel bearing clasts in a highly indurated breccia 15445. These clasts have cataclastic texture but relict unfragmented areas confirm the clasts originally were coarsely crystalline. The mineralogy is essentially olivine + orthopyroxene + spinel + plagioclase. Compositions of mineral phases are given in table 2. Trace element data for one of these clasts showed a rare earth element (r.e.e.) pattern with strong relative enrichment of heavy over light r.e.e. (Ridley *et al.* 1973). This pattern remains unique amongst lunar rocks, and leads to the suggestion that the clasts must originally have contained a high proportion of garnet. This can be achieved by the following reaction: $\text{Mg}_3\text{Al}_2\text{Si}_3\text{O}_{12} + \text{Mg}_2\text{SiO}_4 \rightleftharpoons \text{MgAl}_2\text{O}_4 + 4\text{MgSiO}_3$ which proceeds to the right with decreasing pressure. Hence we suggest the clast assemblage may originally have been pyrope-rich garnet +

lunar crust, possibly as xenoliths in ascending magma. Within the crust they underwent one and probably two phase changes that stabilized spinel and then plagioclase. They were subsequently excavated during the formation of the Imbrium Basin and incorporated into the Imbrium ejecta blanket. We also note that the calculated mode, allowing for the crudeness of the technique, is that of a pyroxenite, consistent with models requiring a pyroxenitic mantle for the Moon.

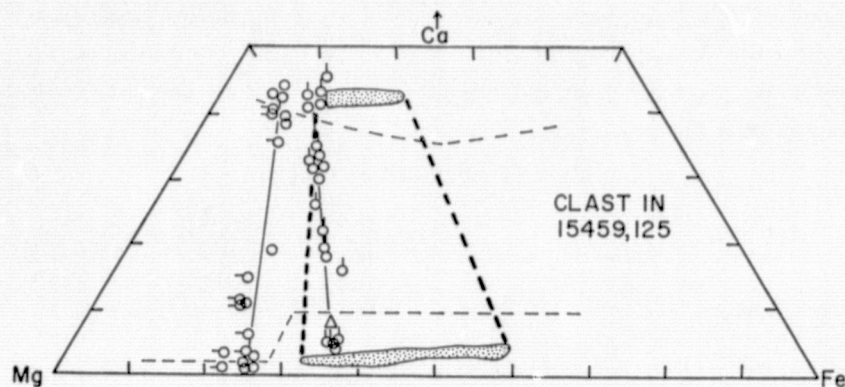


FIGURE 1. Composition of pyroxenes in clasts in breccia 15459. Solid lines are tie lines between coexisting Ca-rich and Ca-poor pyroxenes. Shaded areas are range in composition of exsolved pyroxenes in Apollo 16 breccias. Dashed lines are coexisting pyroxenes from the Skaergaard Intrusion. Circles with vertical bar are inverted pigeonites from a plutonic norite clast. Intermediate compositions represent analyses where the microprobe beam was unable to resolve host and lamellae. Triangle represents bulk analyses of inverted pigeonite. Circles with horizontal bars are exsolved orthopyroxene oikocrysts in a poikiloblastic clast. Circles represent coexisting orthopyroxene and augite chadacrysts in the same clast.

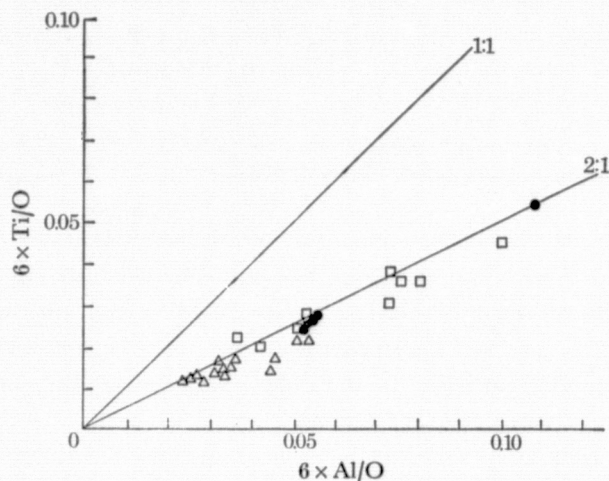


FIGURE 2. Ti-Al relations in pyroxenes plotted in figure 1. Note the close adherence to $\text{Al}:\text{Ti} = 2:1$ line indicating the presence of $\text{R}^{2+}\text{TiAl}_2\text{O}_6$ component. Δ , exsolved inverted pigeonites in plutonic norite; $\square$, exsolved orthopyroxene oikocrysts; $\bullet$, coexisting orthopyroxene-augite chadacrysts in a poikiloblastic clast.

(b) Norite

Breccia 15459 contains clasts composed of coarse grains of calcic plagioclase and orthopyroxene. Coarse exsolution lamellae of augite occur parallel to 100 of the orthopyroxene with earlier exsolution parallel to 001 of an original pigeonite. Table 4 (anal. 9-10) and figures 1 and 2 indicate the chemical relations between pyroxenes in this type of clast. Similar pyroxenes

have been described by Brown *et al.* (1973) from some Apollo 16 breccias, and Papike & Bence (1972) from an Apollo 14 breccia. The observation of pigeonite inverted to orthopyroxene, accompanied by exsolution of augite can be closely matched by terrestrial layered complexes of the Stillwater type. Together with the coarse-texture and simple mineralogy, all these features are consistent with the norites having developed by slow cooling of basic magma within the lunar crust. The bulk composition of the exsolved pyroxene is that of pigeonite with a low TiO_2 content. This contrasts with the titaniferous pigeonites crystallized from mare basalts, suggesting the parent magma was not of mare basalt composition. The presence of abundant plagioclase, together with the low $\text{TiO}_2/\text{Al}_2\text{O}_3$ ratio of the pyroxenes indicates an aluminous magma as a parent.

TABLE 3. SPINELS IN 15459

	1	2	3	4	5	6	7
TiO_2	23.98	23.89	20.13	16.85	54.42	30.24	28.86
Al_2O_3	6.06	6.22	8.11	10.14	0.33	2.40	2.67
Cr_2O_3	16.99	17.74	23.44	26.73	0.49	7.14	8.80
FeO	47.47	47.19	44.00	40.10	40.56	61.18	58.45
MnO	0.39	0.39	0.39	0.36	0.36	0.38	0.35
MgO	3.35	3.40	3.37	3.48	3.92	0.35	0.37
	8	9	10	11	12	13	
TiO_2	50.93	20.03	28.33	52.75	70.09	53.63	
Al_2O_3	0.01	5.36	2.57	0.27	1.61	0.28	
Cr_2O_3	0.37	24.94	7.97	0.11	7.78	0.03	
FeO	46.64	49.83	59.68	40.45	9.18	40.92	
MnO	0.28	0.38	0.38	0.44	0.03	0.47	
MgO	0.47	0.92	0.51	4.16	2.29	4.27	

1-5, Traverse from centre (1) to edge (5) of zoned spinel in, 124 (mare gabbro clast).

6-8, Traverse from centre (6) to edge (8) of spinel in recrystallized anorth. gabbro, 19.

9, 10, Small, individual grains in, 19.

11, Magnesian ilmenite in recrystallized poikilitic breccia.

12, Armalcolite in norite cumulate. Also contains 0.06% SiO_2 , 3.19% CaO , 4.78, ZrO_2 .

13, Magnesian ilmenite in recrystallized breccia, 123.

The pigeonite is more iron-rich than pigeonite crystallized initially from high-alumina basalts and is also associated with rare grains of zirconium-armalcolite (table 3). The latter is chemically distinct from armalcolite precipitated from mare basalts, but none the less reflects a magma with high titania activity. These observations suggest crystallization of the norite minerals from a terra magma already moderately fractionated, but not yet depleted in titanium.

Temperatures of equilibration of orthopyroxene host and augite lamellae can be estimated from the geothermometer of Wood & Banno (1973), resulting in a value of 990 °C. This value is only slightly lower than olivine-clinopyroxene equilibration temperatures estimated for several terrestrial layered intrusions (Powell & Powell 1974).

Since these clasts occur in breccias that are at least 3.9 Ga old, the original norites would have developed whilst the lunar crust was still subjected to largescale meteorite bombardment. Yet the clasts show no evidence for metamorphism or cataclasis, and hence the norites must have developed *beneath* the surface veneer of brecciated rock. The initial period of crustal evolution must have passed into a phase involving a global-scale development of the crust by the formation of true igneous cumulates protected from meteorite bombardment by a gradually

thickening roof. The norites described here may belong to this phase of crustal development and were only excavated because the Imbrian event was unusually intense. As a consequence rocks with pristine igneous textures became intimately mixed with more surficial rocks that had suffered the effects of external bombardment. It is these latter types that are described in the following section.

(c) *Poikiloblastic gabbroic anorthosites*

Several white clasts in 15459 (e.g. 15459, 125 and 123) have well developed poikiloblastic textures defined by chadacrysts of plagioclase, orthopyroxene, pigeonite, olivine and augite

TABLE 4. COMPOSITION OF PYROXENES IN 15459

	1	2	3	4	5	6	7
SiO ₂	54.07	53.06	51.26	51.52	52.54	51.81	50.62
TiO ₂	0.23	0.50	0.87	1.21	0.39	0.76	0.89
Al ₂ O ₃	0.80	1.76	2.30	1.58	0.86	1.69	1.79
Cr ₂ O ₃	0.52	0.70	0.57	0.28	0.38	0.54	0.57
FeO	16.47	15.91	17.92	21.43	19.66	18.89	12.78
MnO	0.29	0.30	0.34	0.35	0.33	0.34	0.33
MgO	24.42	22.30	19.22	17.28	20.94	19.53	15.20
CaO	3.50	5.40	7.54	6.66	4.48	6.07	15.88
Na ₂ O	0.04	0.03	0.06	0.05	0.03	0.03	0.05
Si	1.969	1.948	1.915	1.942	1.965	1.941	1.933
Ti	0.006	0.014	0.025	0.034	0.011	0.021	0.026
Al	0.034	0.076	0.101	0.071	0.038	0.075	0.081
Cr	0.015	0.020	0.017	0.009	0.011	0.016	0.017
Fe	0.502	0.489	0.560	0.675	0.615	0.542	0.408
Mn	0.009	0.009	0.011	0.011	0.011	0.011	0.010
Mg	1.326	1.221	1.070	0.971	1.167	1.091	0.365
Ca	0.137	1.213	0.302	0.269	0.180	0.244	0.650
Na	0.003	0.002	0.004	0.004	0.002	0.002	0.003
Al-Cr/Ti	3.06	4.03	3.43	1.80	2.37	2.73	2.48
	8	9	10	11	12	13	14
SiO ₂	50.39	53.86	51.43	52.00	53.23	53.88	50.85
TiO ₂	1.90	0.83	1.23	0.50	0.44	0.97	2.15
Al ₂ O ₃	2.50	1.22	1.74	1.00	0.76	1.54	2.91
Cr ₂ O ₃	0.35	0.37	0.43	0.45	0.29	0.29	0.39
FeO	13.25	15.71	6.69	8.59	21.34	15.28	7.84
MnO	0.32	0.25	0.13	0.22	0.37	0.28	0.15
MgO	13.74	26.90	17.68	15.27	22.72	26.12	17.62
CaO	16.81	1.16	18.69	19.87	1.45	1.89	16.56
Na ₂ O	0.09	0.06	0.22	0.13	0.03	0.92	0.18
Si	1.908	1.943	1.921	1.967	1.966	1.944	1.890
Ti	0.054	0.023	0.036	0.014	0.012	0.026	0.060
Al	0.112	0.052	0.077	0.045	0.033	0.066	0.127
Cr	0.010	0.011	0.013	0.013	0.009	0.008	0.011
Fe	0.420	0.474	0.209	0.272	0.659	0.461	0.244
Mn	0.010	0.008	0.004	0.007	0.012	0.009	0.005
Mg	0.776	1.447	0.984	0.861	1.251	1.405	0.976
Ca	0.682	0.045	0.748	0.806	0.058	0.073	0.660
Na	0.006	0.004	0.016	0.009	0.002	0.001	0.013
Al-Cr/Ti	1.88	1.82	1.84	2.21	2.00	2.17	1.92

1-4, Typical zoning trend from core (1) to rim (4) for pigeonite in, 124 mare gabbro.

5-8, Typical zoning trend from core (5) to rim (8) of pigeonite-augite in, 124 mare gabbro.

9-10, Orthopyroxene (inverted pigeonite) host (9) to exsolved augite (10) in norite cumulate clast in, 125.

11-12, Host orthopyroxene (12) to finely exsolved augite (11) as oikocrysts in poikilitic clast in, 125.

13, 14, Homogeneous grains of orthopyroxene (13) and augite (14) in recrystallized, poikilitic clast in, 125.

surrounded by oikocrysts of unzoned orthopyroxene. Analyses of oikocrysts and chadacrysts are shown in table 4 and figures 1 and 2. The orthopyroxene oikocrysts contain thin exsolution lamellae of augite on (100). Crystallographic studies indicate the orthopyroxene has inverted from original pigeonite (Takeda 1972), but no (001) lamellae were observed. Exsolved oikocrysts are rarely observed in lunar poikiloblastic rocks, most of which are weakly zoned orthopyroxene or pigeonite (Simonds *et al.* 1973; Bence *et al.* 1973). McCallum *et al.* (1974) have described large orthopyroxene oikocrysts with coarse augite lamellae in gabbroic anorthosite 77017, and submicroscopic exsolution has been detected in 67955 (Hollister 1973). Presumably differing rates of cooling and varying bulk compositions result in the varying types of oikocrysts observed in lunar breccias.

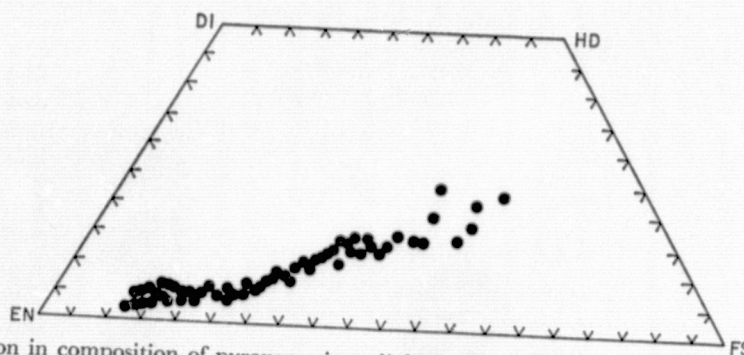


FIGURE 3. Variation in composition of pyroxenes in a diabasic-textured krep norite clast 15459, 19. Note the continuity of pyroxene compositions from cores of aluminous bronzite to rims of intermediate pigeonite.

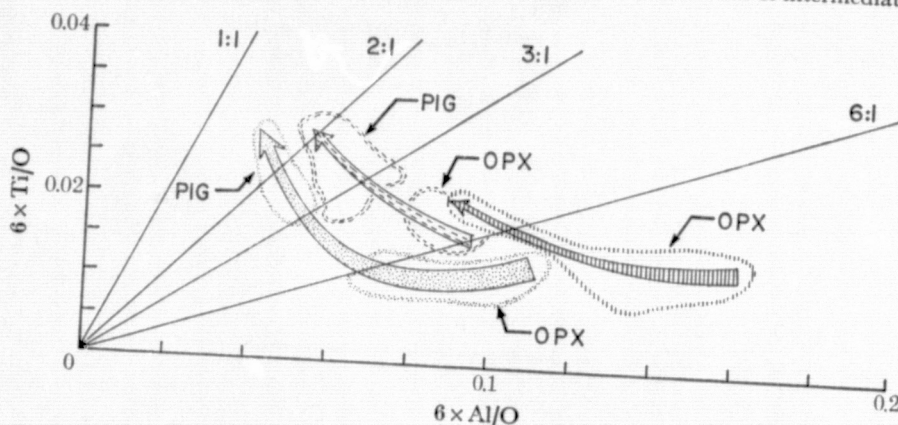


FIGURE 4. Ti-Al relations in pyroxenes plotted in figure 3. Note the core bronzites have Al:Ti > 6:1 indicating the presence of $R^{2+}Al_2SiO_6$ component reflecting high alumina activity in the basalt melt. During crystallization the Al:Ti ratios approach 2 and in some crystals < 2 suggesting the presence of divalent Cr or trivalent Ti.

The environment for formation of these poikiloblastic rocks is not well defined, although they are clearly widespread in the lunar highlands. Terrestrial experience indicates poikilitic textures may be produced by direct crystallization from a silicate melt or by subsolidus recrystallization during contact metamorphism. Similar textures are observed in terrestrial impact melts (Grieve *et al.* 1974), so that poikiloblastic lunar rocks may similarly be the product of meteorite bombardment. Nonetheless, much controversy has arisen over the interpretation of lunar poikiloblastic rocks in terms of an igneous versus metamorphic origin.

Temperatures of equilibration of minerals in some poikiloblastic rocks can be estimated by using several pyroxene geothermometers, and the olivine-clinopyroxene geothermometer (Powell & Powell 1974). For 15459, 125 clasts the following temperatures (with largely unknown errors) were calculated: exsolved orthopyroxene oikocrysts: 1060 °C, orthopyroxene-augite chadacrysts: 1099 °C, olivine-augite chadacrysts: 990 °C. The presence of inverted pigeonite indicates cooling through the clinopyroxene-orthopyroxene inversion temperature. Extrapolation of the curve of Brown (1968) for $W_0 = 7.6-8.9$ suggests a temperature below 1100 °C, consistent with those calculated above.

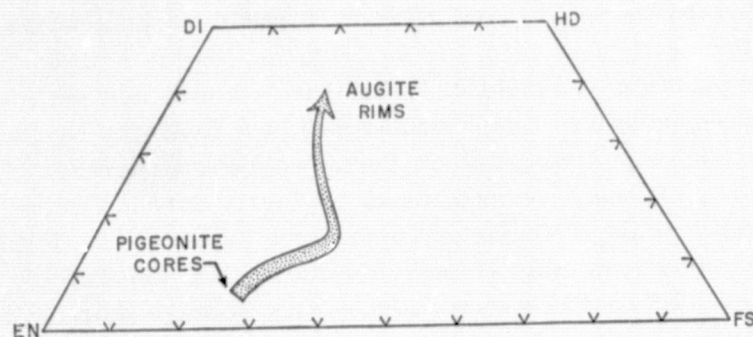


FIGURE 5. Zoning trend in clinopyroxenes from mare gabbro clast 15459, 124. There is a gradual change from core pigeonite, low-Ca augite to rims of augite with relatively minor non-enrichment. This contrasts with the strong iron enrichment in pyroxenes from Apollo 15 mare basalts, reflecting different rates of cooling.

We note that McCallum *et al.* (1974) estimated the crystallization temperature of 77017 to be 1050–1100 °C, and a temperature estimate based upon olivine-augite equilibrium gives 1010 °C. Temperatures calculated for other poikiloblastic rocks are as follows:

Diabasic areas in 60315, 63: 1102 °C (opx-cpx), 1072 °C (ol-cpx)

Poikiloblastic area in 60315, 63: 1254 °C (opx-cpx)

67955: 1093 °C

Generally, poikiloblastic rocks appear to have crystallized below 1100 °C. Even allowing for the variations in composition of individual rocks (they vary from 'creep' basalt to anorthositic gabbro), this is well below the liquidus temperatures. Hence we prefer the interpretation that most poikiloblastic rocks crystallize in a metamorphic condition, possibly allowing for the presence of 5 % intergranular fluid.

(d) Mare gabbro

Post-Imbrium reworking of 15459 is suggested by the presence of clasts of coarse mare gabbro, whose mineral chemistry is similar to the local 3.5 Ga mare basalts (tables 3, 4; figure 5). The gabbros are composed of zoned clinopyroxene + olivine + plagioclase + spinel + ilmenite. It is interesting to note that such coarse samples were not observed among the sampled mare basalts, but they can be chemically and texturally interpreted as the slowly-cooled equivalents of the olivine-normative mare basalts. At least some of the variation observed among the olivine basalts from Palus Putredinus has been ascribed to low-pressure fractional crystallization (Rhodes & Hubbard 1973). The presence of gabbro clasts clearly suggests that mare basalt magma did cool slowly enough to allow fractional crystallization to proceed.

SUMMARY

Breccias collected from the rim of Spur Crater contain several distinct types of clast, most of which are stratigraphically related to the terra crust and presumably represent parts of the pre-Imbrium crust. Studies of the matrix components of one breccia, 15459, are consistent with it having developed by consolidation of a soil similar to the local soil along the Apennine Front.

Ultramafic clasts in breccia 15445 can be interpreted to originally contain garnet and are considered to have been garnet pyroxenites from the lunar mantle. Early volcanism may have introduced the pyroxenites into the crust as xenoliths where they underwent low-pressure subsolidus re-equilibration.

Another clast population of plutonic norites have textures and mineral characteristics found in Stillwater-type layered complexes and may have developed by slow cooling within the terra crust beneath a protecting thick roof of impact-brecciated rock.

Yet another group of clasts have poikiloblastic textures as a result of impact metamorphism and may be members of the rock suite that formed the highly brecciated, shocked, annealed and recrystallized outer terra crust. However they differ from poikiloblastic rocks described from Apollo 16 and 17, in having several chadacryst phases and numerous unresorbed clasts. This and other textural evidence favour formation at lower temperature, followed by relatively slow cooling.

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REFERENCES (Ridley)

- Bence, A. E., Papike, J. J. & Delano, J. W. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 4, 597-611.
- Brown, G. M., Peckett, A., Emeleus, C. H., Holland, J. G. & Phillips, R. 1973 *Lunar Sci.* 4, 94-96.
- Green, D. H. & Ringwood, A. E. 1967 *Contrib. Mineral. Petrol.* 15, 103-190.
- Grieve, R. A. F., Plant, A. G. & Dence, M. R. 1974 *Proc. Fifth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 5, 261-273.
- Kushiro, I. 1972 *Lunar Sci.* 3, 466-468.
- Hollister, L. S. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 4, 633-641.
- McCallum, I. S., Mathez, A. E., Okamura, F. P. & Ghose, S. 1974 *Proc. Fifth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 5, 287-302.
- Meyer, H. O. A. & Boyd, F. R. 1972 *Geochim. cosmochim. Acta* 36, 1255-1274.
- Papike, J. J. & Bence, A. E. 1972 *Earth Planet. Sci. Lett.* 14, 176-182.
- Powell, M. & Powell, R. 1974 An olivine-clinopyroxene geothermometer. *Contrib. Mineral. Petrol.* 48, 249-263.
- Prinz, M., Dowty, E. & Keil, K. 1973 *Geochim. cosmochim. Acta* 27, 979-1006.
- Reid, A. M. & Dawson, J. B. 1972 *Lithos* 5, 115-124.
- Reid, A. M., Warner, J., Ridley, W. J. & Brown, R. W. 1972 *Meteoritics* 7, 395-415.
- Rhodes, J. M. & Hubbard, N. J. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 2, *Geochim. cosmochim. Acta Suppl.* 4, 1127-1148.
- Ridley, W. I., Hubbard, N. J., Rhodes, J. M., Weismann, H. & Bansal, B. 1973 *J. Geol.* 81, 621-631.
- Ridley, W. I., Reid, A. M., Warner, J. L., Brown, R. W., Gsoley, R. S. & Donaldson, C. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 4, 309-321.
- Simonds, C. H., Warner, J. L. & Phinney, W. C. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 4, 613-632.
- Takeda, H. 1973 *Proc. Fourth Lunar Sci. Conf.* vol. 1, *Geochim. cosmochim. Acta Suppl.* 4, 875-885.
- Wood, B. J. & Banno, S. 1973 *Contrib. Mineral. Petrol.* 42, 109-124.

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